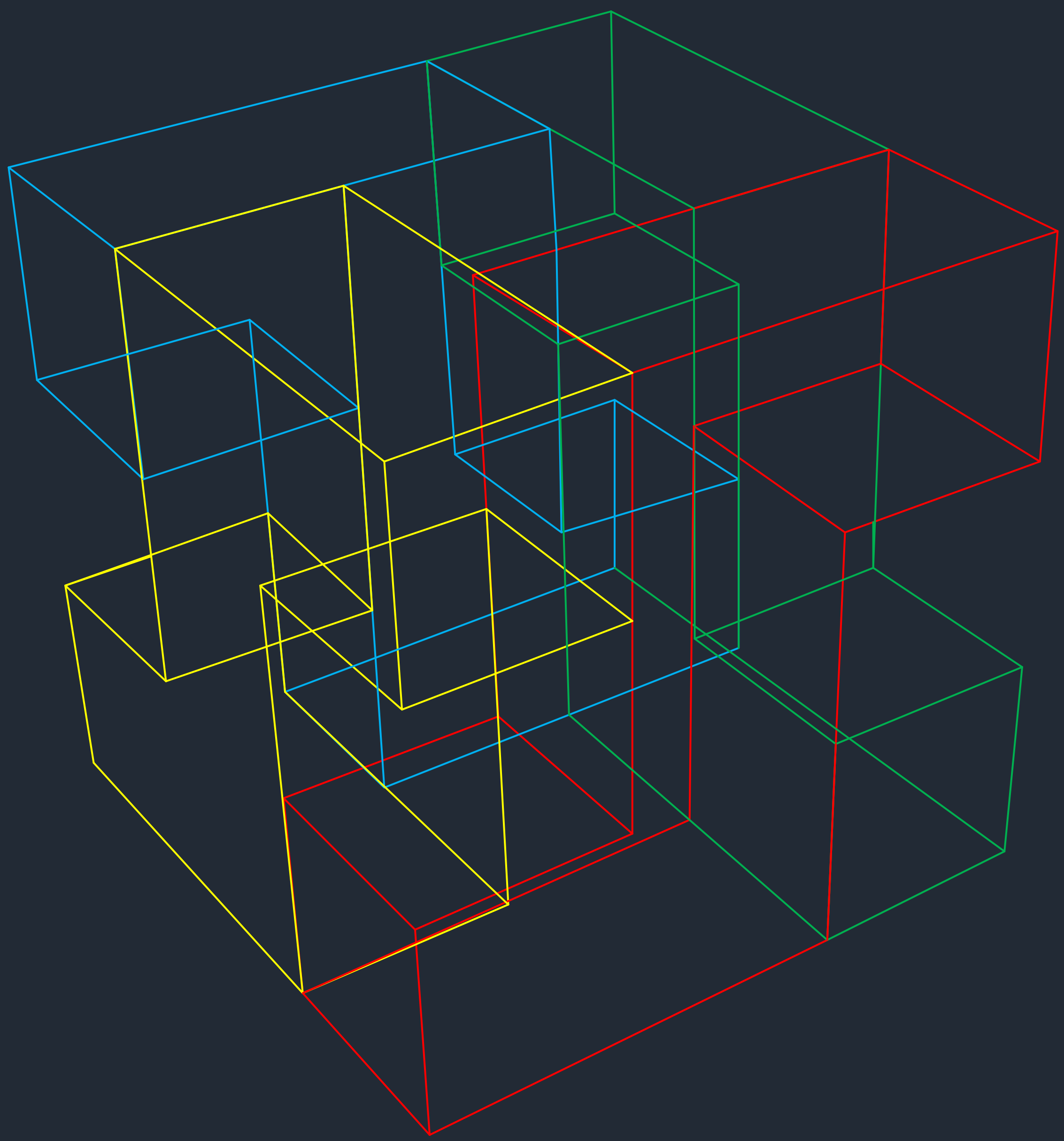
Glass columns

Structural analysis on replacing existing columns with glass



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Preface

Before you lies the thesis written in partial fulfilment for the bachelor program of Civil Engineering at the TU Delft. The program finishes by conducting a thesis. This research is written from 16th of November 2017 to 19th of January 2018.

Rarely occurs the possibility to design something from scratch during my study and that is something that I sometimes miss as an engineer. Additionally, working with glass is also interesting as I have not done that before. That is the reason why I chose this subject.

The research was exciting and fun and I would to deeply thank my two supervisors Telesilla Bristogianni and Rob Nijsse for their time, support and guidance. Both are very talented and knowledgeable about glass and their passion is something that struck me.

A special mention to my parents, sister and girlfriend for their support and proofreading.

Yat Long Liu
January 2018, Delft

Abstract

Not many glass columns exists in the world, and especially used for buildings. Safety and mass manufacturing is a problem. How can you make sure that a glass column is safe even enough for the public and in what way can it been manufactured? These are two of the seven problems I am faced with during my research. The purpose of this thesis is to look the possibilities of using glass columns to replace the existing concrete columns of the 1st floor of the Civil Engineering faculty at the University of Technology in Delft.

First, a study about the different properties of glass will be conducted to gain enough knowledge for designing a glass column.

In a detailed central section the research presents methods on how to build a column made of modified Tetris shapes.

In conclusion, the results suggests that it depends on the design as some methods are more efficient than the other. Casted glass is often for unusual and irregular shapes. However, it takes a long time for glass to cool down after manufacturing and therefor often expensive in comparison with laminated glass. The latter method is used for the Tetris design.

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1. Introduction

Transparent, hard, brittle and elegant. Glass is a beautiful yet fragile material. The aesthetic value of glass is very important in the engineering world. With constantly improving functions and utilizations techniques, it is one of the most useful and fascinating material used in the area of civil engineering, besides concrete and steel.

Glass appears in lots of styles and forms, one of such being columns. Columns, generally made from concrete and steel, are needed to give stability and support to the construction. However, it also blocks the vision of the viewer. A solution for this is glass columns, so that the viewer will be able to look through a column. Although satisfying both the architectural and structural aspects, the use of glass has some disadvantages.

Figure 1.1 Glass column concept, Danteum, by Giuseppe Terragni.

There is a great difference by using glass column compared to the more traditional form. Glass is vulnerable to many things such as imperfections on the surface, a simple scratch may potentially decrease the quality and strength. Also, there is a big difference between compressive and tensile strength. However, the main reason for why glass is not used as a standard material is the brittleness. Once a crack or fracture appears the whole column will quickly lose its strength and stiffness if not dealt with the problem in the early stages.

1.1 Project Definition

Glass columns generally consist of curved or flat glass plates, or extruded standardized profiles. This method limits the form of the column as they are often laminated together with multiple layers and interrupt the transparency.

1.2 Problem statement

For this research I will use the existing concrete columns of the 1st floor of the Civil Engineering faculty at the University of Technology in Delft as my case study. I will examine the plausibility of using cast glass elements as an answer to the current limitations in shape and transparency and to replace the concrete columns with the my glass column design.

1.3 Objectives

The objective of this research will be divided into seven sub-goals:

Criteria	Description
1. **Shape**	How elegant is the glass column that blends in the architectural language of the construction?
2. **Sizing**	How much area is needed for the glass column?
3. **Manufacturing**	How long does it take to manufacture the glass component and what are the relative costs?
4. **Assembly**	How difficult is it to make the glass component (make ability)?
5. **Connection**	How structural and aesthetically pleasing are the connecting components for the glass column with each other, the foundation and the top?
6. **Transparency**	How transparent is the column?
7. **Safety**	How is the safety of the glass column when it fails?

Table 1.1 The objectives of the research divided into seven sub-goals.

1.4 Scope

Limitations, simplifications and assumptions are needed to be made to narrow down the scope. The final design of the glass column will be based on replacing the existing ones of the faculty of Civil Engineering. Research will be done based on already experiments with glass columns to obtain the information and data needed for further calculations and estimations (such as the height of the column, the foundation, weight of the roof). If these are not available, an estimation will be made based on similar projects.

2. Glass

Glass is one of the most widely used material, presently. The use of glass columns in the structural field is still in its experimental phase. From an architectural viewpoint these columns gives a more beautiful and transparent perspective. Different shapes and sizes can be created with endless possibilities. However, this also presents a few design problems for the engineer. In this chapter I discuss the different chemical and mechanical properties of glass of how some of these will affect if used in a structure.

2.1 Chemical properties

The most common form of glass is Soda-Lime, referring to its second and third major ingredients. Soda-Lime is made of the following materials: silica (SiO2), soda or sodium (Na2O), lime or calcium oxide (CaO), magnesia (MgO), and aluminum(III) (Al2O3). (Warm Glass UK, 2013)

Silica is a natural compound made of silicon and oxygen. Its main components are sands and rock, which are fundamental ingredients of glass. Soda or sodium is a flux, which lowers the melting temperature of sand from 1815°C to 1370°C. Unfortunately, this will make glass unstable as a product. Therefore we use lime or calcium oxide to chemically stabilize glass and gives its hardness.

The materials of glass are isotropic, which means they possess the same properties independent of the direction. The chemical bond of electrons in glass does not absorb light, thus light passes through glass. These two properties gives the transparency of glass. (Thijsse, 2015). Other ingredients can be added to glass, such as magnesia and aluminum(III) to modify its melting temperature, hardness and strength.

2.2 Mechanical properties

It is very challenging to find a general norm to calculate the strength of glass due to the many different factors that can influence the supposed strength of glass.

Glass is very strong as it has strong covalent bonds. Theoretically, the tension strength can yield up to 17.000 MPa. Comparable to the pressure needed for the first commercial synthesis of diamond (Schmetzer, 2010). However, the practical tensile strength is much lower, as a result glass is a brittle material and can be very fragile. This is characterized as the rupture happens without prior notice in the rate of elongation. So glass behaves elastic until the moment it fractures as it has no yield point. (Beer et al, 2009)

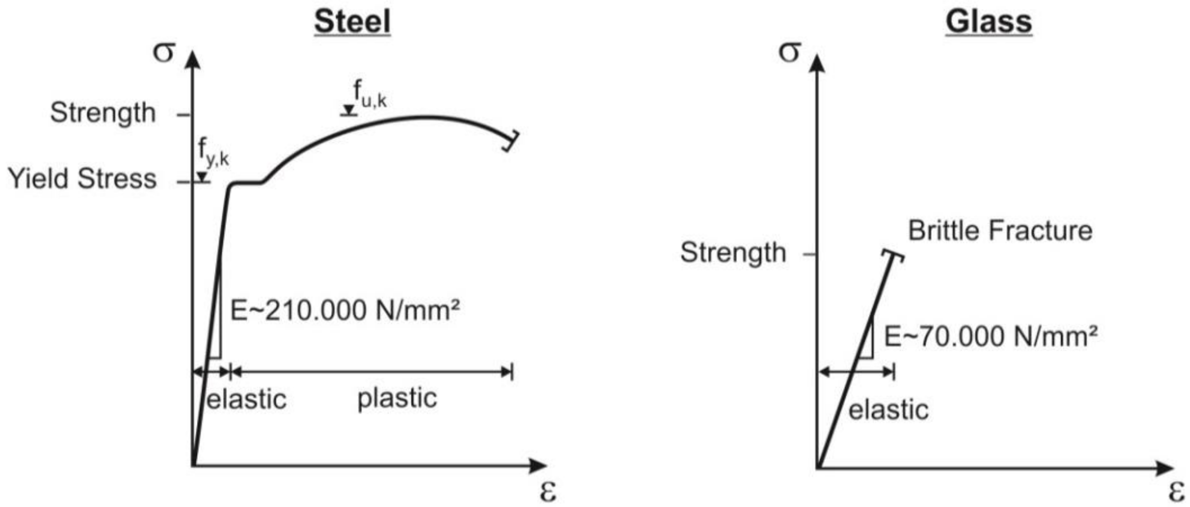


Figure 2.1 Stress-strain of steel and glass.

2.2.1 Weakness

Glass performs poorly if exposed to long-term load. An experiment was done on a glass window under load with a difference in duration: 5 seconds and 3600 seconds. This resulted a difference between the load capacity of 34%. The window became a third after an hour. However, after the removing the load the window recovered to almost all of its original strength.

The type of load is also of great influence on the fragility of glass. Wind-load strongly varies over intensity and time, snow-load is static and present for longer time and glass on the floor (walkable glass) need to be calculated with a load duration of fifty years. It is also fragile to withstand a suddenly applied load of force. (Kruijs, 2009)

A small flaw on the surface such as scratches, bubbles, inhomogeneities or inclusions is enough to decrease its strength. These are often not visible with the naked eye.(Lehman). If a wind blows against the surface of glass, that area will become slightly damaged with microscopic scratches. At that same area, there will be tensile stress on the surface and tensions arise at the bottom of the scratch. A chemical process is established that makes the scratch deeper through a combination of moisture and tensile stresses. This process is responsible for weakening the glass over time and could eventually grow into cracks. (Shelby, 2005) However, these surface scratches are often so miniscule that they do not affect the structural performance.

2.2.2 Strengthening

There are three fundamental process which can strengthen glass: tempering, thermal heating and chemical strengthening. These will increase the overall strength and the heat resistance of the glass. Before that I need to address the annealing process.

2.2.2.1 Annealing

Annealing, a process of gradually controlled heating and cooling the glass, is a common method and nearly implemented in each production of glass. This process allows the outer surface of the glass to cool down at the same speed as inner surface. This is done by a moving metal belt which goes to an annealing oven. The glass behavior is perfectly elastic until the moment of fracture. The whole process of annealing varies greatly from a few hours to years as it depends on the size of the object.

2.2.2.2 Tempered

Tempered glass is a process by managing thermal treatments to increase the strength compared with normal glass as it puts the outer surface into compression and the inner surface to tension. This is done by placing the glass on a roller table which goes through a furnace. The furnace has a temperature up to 720°C. Glass that comes out of the furnace is quenched with cold air. This causes the glass to gain stresses within the material, as the surface is cooled much quicker than the inner part.

2.2.2.3 Heat

This process is done by heating the glass to 600°C and rapidly cooling down. The outer surface will be in a dilated phase and the inner surface retract as the temperature decreases, thus creating compressive strength on the outer layers and tension in the inner layer. This whole process is similar to tempered glass, though varying in temperature, quenching parameters and cycle times. (Abrisa Technologies, 2010)

2.2.2.4 Chemical

The glass is put into a potassium salt bath at 300°C. The surface of the glass contains sodium ions which then will be replaced by potassium ions from the bath solution. Note that sodium ions are smaller than the potassium ions. The potassium ions stuff itself into the smaller gaps when it replaces the sodium ions. This causes compressive stress on the glass surface to reach up to 690 MPa. Chemically strengthened glass is not sensitive to severe changes of temperature and is often applied in thin glass panels.

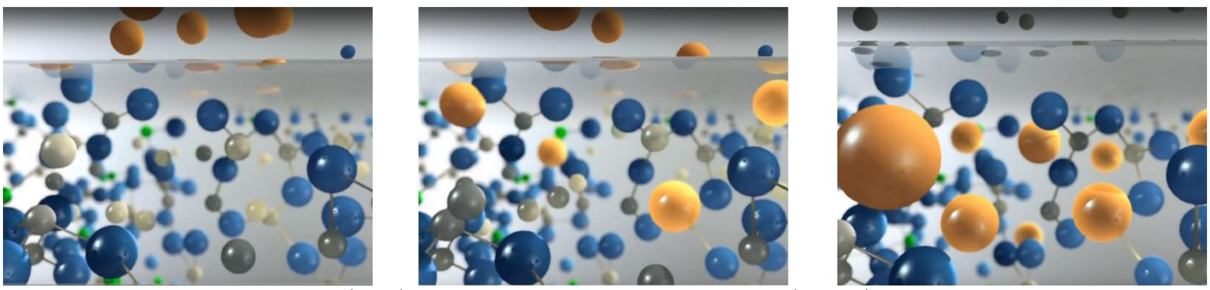


Figure 2.2 Sodium ions (blue) being replaced by potassium ions (yellow).

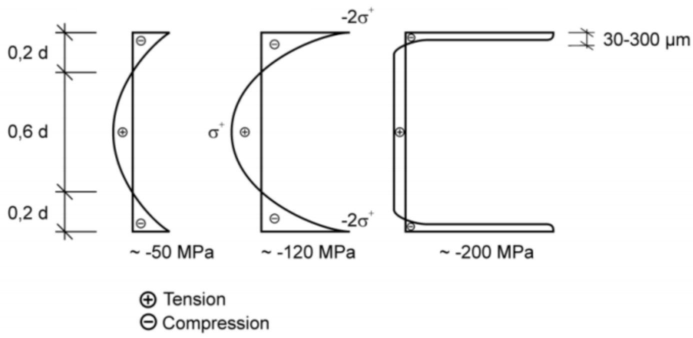


Figure 2.3 Heat strengthened, fully tempered, chemically strengthened (from left to right).

Propery	Heat Tempering Change	Heat Strengthening Change	Chemical Strengthening Change (8 hours)	Chemical Strengthening Change (16 hours)
Impact Resistance*	5 to 6x	N/A	3 to 4x	4 to 5x
Bending Strength*	4 to 5x	2x	3,5x	2,5 to 3x
Resistance to Temperature*	4x	2,5x	1,8 to 2,5x	1,8 to 2,5x
Vickers Hardness*	N/A	N/A	1,4x	1,4x
Maximum Temperature	243 °C	230 °C	300 °C	300 °C
Compressive Stress at Surface	>69 MPa	24 MPa to 69 MPa	165 MPa	220 MPa

*Table 2.1 *Relative increase over annealed glass. 5x means 5 times greater (Abrisa Technologies, 2010).*

2.3 Manufacturing and assembly

In this part I will do research on the manufacturing and assembly of 5 different glass types: float, cast, extruded, 3D and flexible glass.

2.3.1 Float glass

The most common type of glass is float glass. The glass literally floats during the manufacturing process, hence the name. Sir Alistair Pilkingston invented this method in 1952 and is worldwide the most popular and widely used process of glass, accounting for almost 90% of today's production of float glass. This process consists of various steps. Raw materials are checked for their quality and quantity and mixed into various batches. These goes through a furnace of 1500°C where the materials are melted and refined together. The melted glass flows over the refractory onto a molten tin at 1150°C and leaves the metal float bath at 600°C. Optionally, a coating can be applied that make subtle changes in optical properties by high temperature to the glass surface. This is often done for making reflective glasses. The next step is to make the float glass ready to be cut. This is done by annealing where internal stresses are removed. A final inspection is needed to guarantee the quality of the float glass like a sand grain that did not melt or a bubble that was not removed during cleansing. The product is then ready to sold to the customer. (Asahi India Glass Limited, 2014)

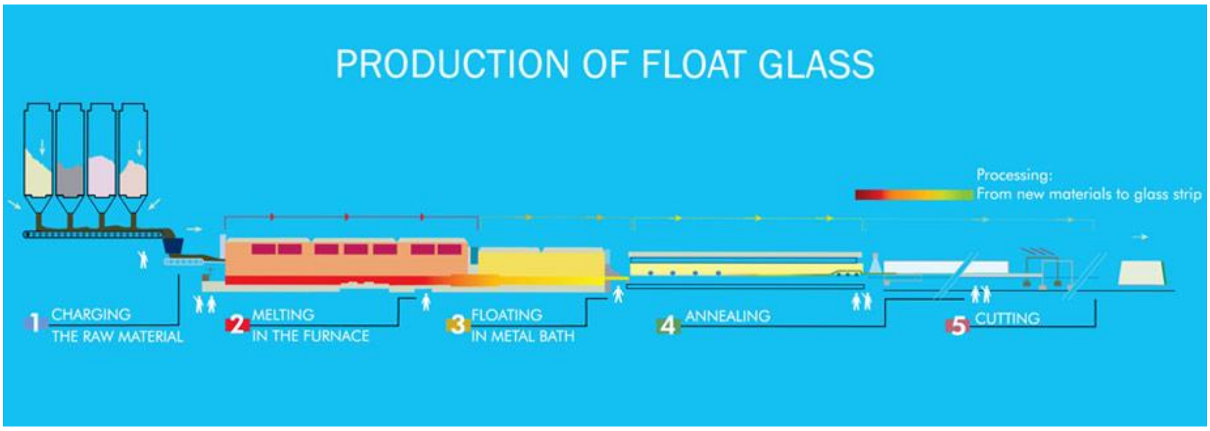


Figure 2.4 The production of float glass by Sir Alistair Pilkingston.

2.3.2 Cast glass

The casting technique creates the possibility for more complex forms like design elements to be fused with other materials. Most common forms are glass bricks and blocks. This is manufactured by pouring molten glass into the mold which then is placed into an oven with a temperature between 800°C and 1000°C, often called a kiln. The mold and the kiln has to been clean thoroughly as it can contain dust and other remainder of previous projects, also it is essential to put enough molten glass into the mold as the glass level drops during the process. The finished product will be about half the depth of the filled mold. It is preferable to fill the mold with large pieces of glass placed vertically to maintain enough glass for the mold to be filled. The molten glass is slowly cooled down to avoid cracks and removed from the mold afterwards. (Glass Campus)

Figure 2.5 Casted glass.

2.3.3 Extruded glass

'Short' glass, glass that quickly crystallize and that melts at a relatively high temperature, are often used for this extrusion technique as you can manufacture different profile sizes of tubes and rods. Outside diameters varying from 0.9 mm to 460 mm and lengths of 0.3 mm to 10 meters. These type of glass has high resistance for chemical, hydrolytic and thermal shock. This process is done by a computer controlled extruder which allows for manufacturing the tubes and rods. (SCHOTT, AG,2017)

Figure 2.6 Different shapes of extruded glass.

2.3.4 3D printed glass

Nowadays 3D printers can print objects with materials such as metal, ceramic and plastic. German researchers from the Karlsruhe Institute of Technology found a new method to print glass objects. The special 'liquid glass', developed by the team, is a nanocomposite with glass nanoparticles suspended in a photocurable prepolymer.

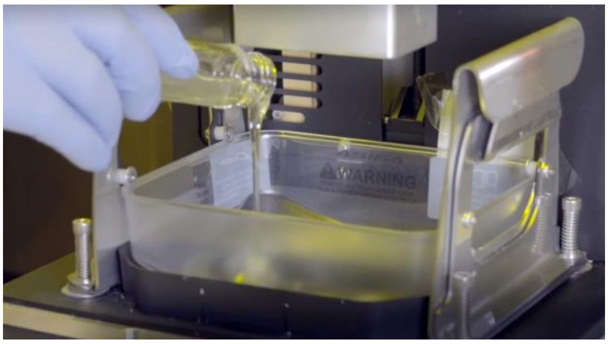


Figure 2.7 Liquid glass.

The glass nanoparticles are mixed into a liquid substance which is used as ink for the 3D printer. After printing, the glass object is placed in an oven where it cures the glass and burns away excess materials. To demonstrate the possibility of printing 3D objects with glass the researchers printed a tiny pretzel, honeycomb and tiny castle and to show its potential. (Kotz et al, 2017)

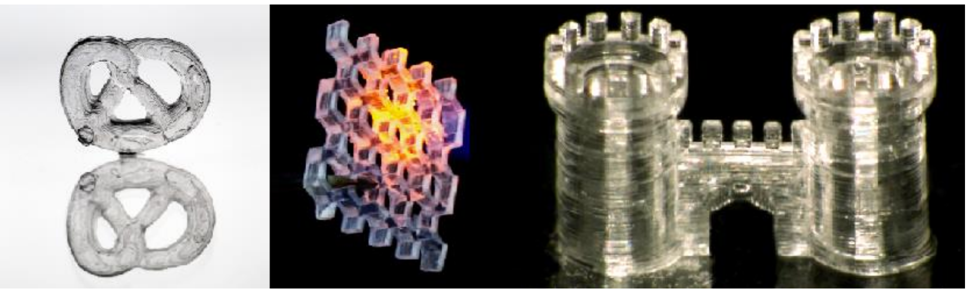


Figure 2.8 3D printed glass objects. Pretzel, honeycomb and castle (from left to right).

2.3.5 Flexible glass

Corning, a glass company in the United States, manufactured a lightweight, conformable and ultra-thin glass. Resulting a unique ability, flexible glass. Thickness varies from 100 to 200 micron with a wideness up to 1.3 meters and 300 meters in length. This flexible glass can protect sensitive materials from staining, oxygen and moisture. The product is still in its experimental stages, but new technological inventions can be made with flexible glass such as a bendable smartphone or a TV screen. (Corning, 2017)

Figure 2.9 Application of bendable glass (smartphone and LCD screen).

2.4 Connections

Here I researched on connections used in glass: clamp, bolt and adhesive.

2.4.1 Clamp

Clamp connection is often used in glass panels. The glass is clamped to the edges or corners. To prevent direct connection a material such as elastomer is applied between the glass and the clamp as this can damage both components. The loads on the glass surface are taken care of by support points or consoles.

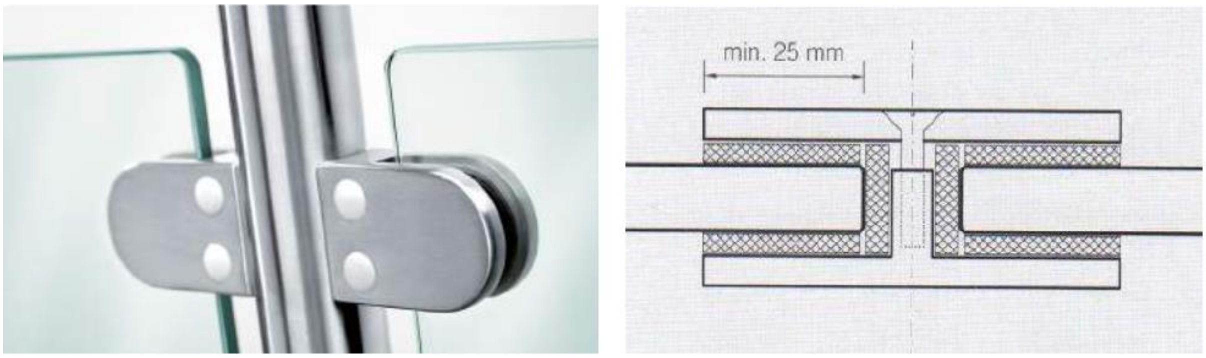


Figure 2.10 Clamped connection.

2.4.2 Bolt

A bolted connection consist of two discs that are clamped to the glass by a bolt. This method is also called button fixing. The loads are transferred by contact between the discs and glass plates. During assembly a quick drying subsistence like resin or grout is applied in the cavity between the bolt and glass.

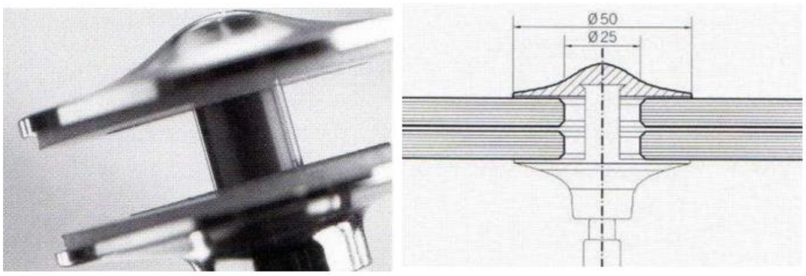


Figure 2.11 Bolted connection.

Another example of a bolted connection is a prestressed bolt connection. As the length of a glass piece if often limited to 6 x 6 meters for practical reasons. To achieve larger and greater spans, multiple beams can be connected together with the help of a prestressed bolt connection. It can be applied in places where the moments or transverse forces are equal to zero. This method is often applied for monolithic tempered glass plates. A disadvantage is the creep behavior of resin/grout, as it can prevent the prestressed bolt from functioning properly with glass.

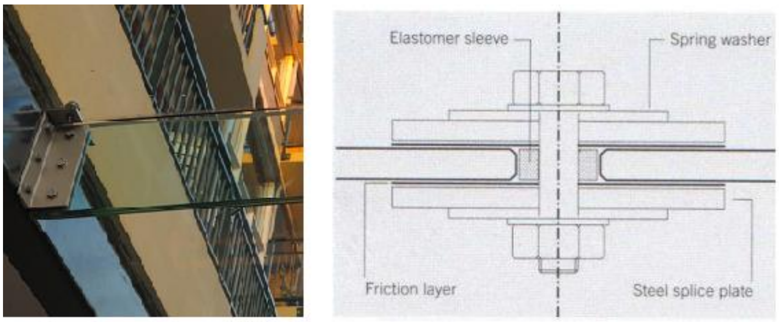


Figure 2.12 *A bolted connection on a marquise.*

2.4.3 Adhesive

Adhesive connection, also known as glued connections, has a wide range of application use. The strength of these connections is determined by the transition between the parts that needs to be connected and the middle layer and by the cohesion of the intermediate layer itself. The adhesive connection is waterproof. There are many factors that can decrease adhesive strength, such as the glue type, shape and thickness of the middle layer, the execution process, load duration, age, fatigue and environmental influences (UV radiation, humidity and temperature). Different type of loads on the adhesive connection contributes to a different tension distribution.

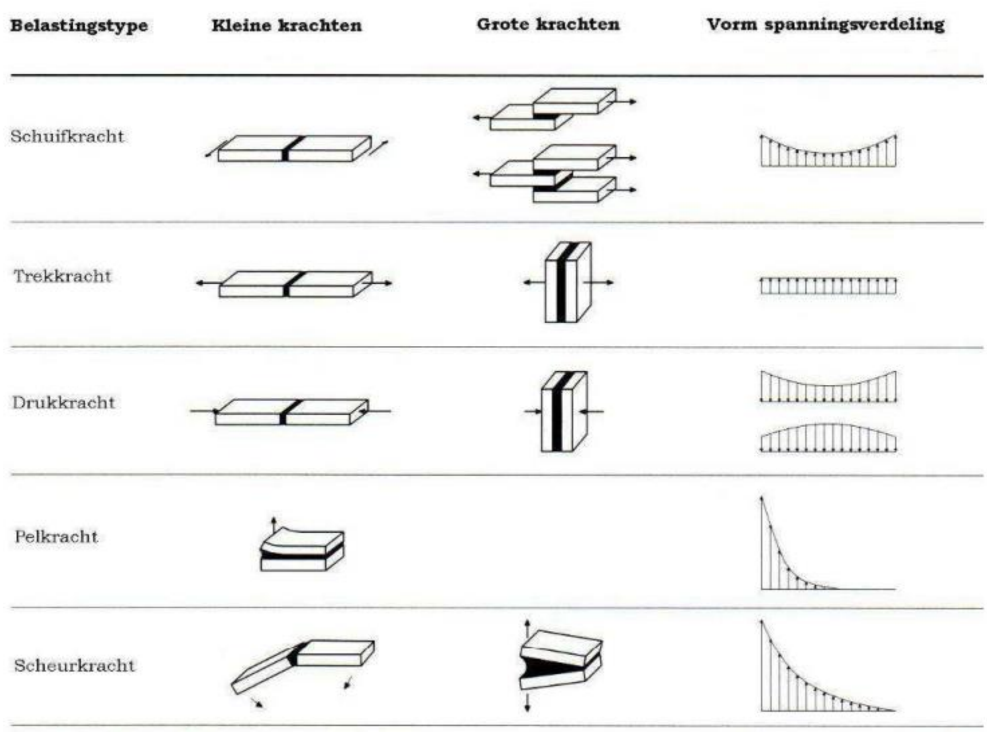


Figure 2.13 *Different type of loads on the adhesive connection.*

2.5 Safety

There are no regulation for glass used as a column. We often use a safety factor of 4. However, it strongly depends on the type of glass. For example the safety factor of annealed wind glass under wind load varies between 3,0 to 9,1 (Bos et al, 2012).

2.5.1 Breaking pattern

Strengthened glass have their own breaking pattern as they all have their distinctive amount of energy released at the moment of failure. Here we discuss the breaking patterns of annealed, heat strengthened and fully tempered glass. The annealed and heated glass breaks easily and produces long sharp splinters and shards. The tempered glass breaks the favorable as the glass shatters completely under high levels of impact energy, and few pieces remain in the frame. The load capacity of the glass is then almost no longer dependent on the load time. This makes it as one of the safest type of strengthened glass. As a result, tempered glass is used in a many applications, including shower doors, refrigerator trays, mobile screen protectors, divings maskers, glass tables and doors.

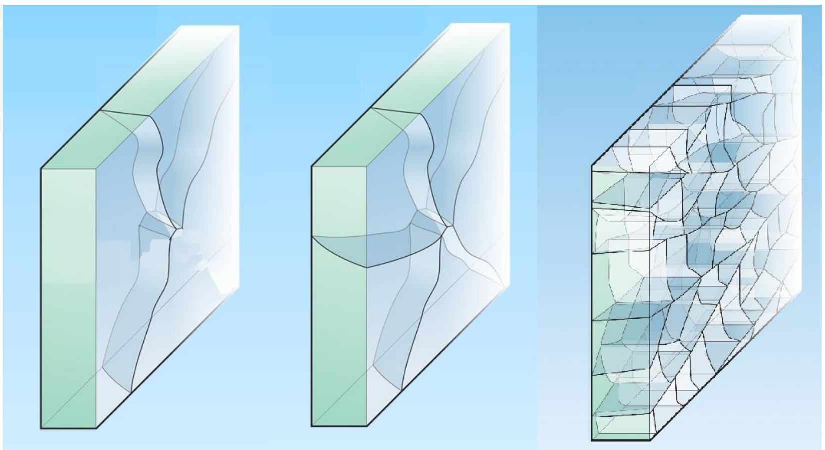


Figure 2.14 Break patterns for annealed (left), heat strengthened (middle) and fully tempered glass (right)

2.5.2 Laminating

Laminated glass consist of multiple plies of glass bonded with a resin middle layer. This glass sandwich tend to stay together if one of them is broken as the outer layer is bonded to the inner layer. Laminated glass isolates sound/noise, blocks up to 99 percent of the UV-light transmission and can be burglar- or bullet-resistant if it is thick enough. It holds up the impact much better than fully tempered glass and prevents the shattering apart due its integrity. Laminated glass is often applied by car windshields.

Figure 2.15 Concept of laminated glass and its breaking pattern

2.5.3 Steel reinforcement

This method transfers the tensile forces from the glass upon breaking at failure to the supporting structure. This concept is integrated in the design of the construction. Another example are wired glasses, where welded steel wire is fixed between the glass layers. Commonly used for fire-rated windows and doors, but also for privacy purposes. In case of breakage, the steel wires retains the pieces of glass. (ALL Purpose Glazing, 2017)

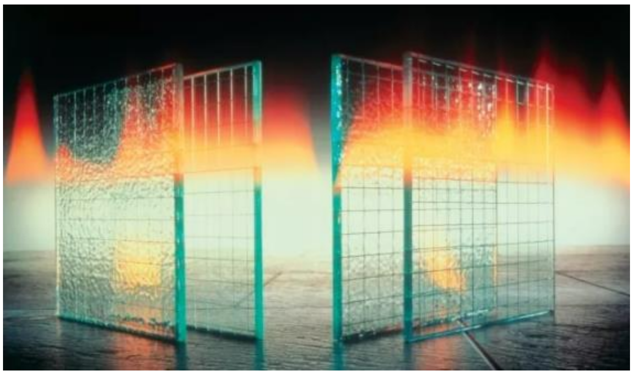


Figure 2.16 Wired glasses.

In the next chapter I will give information about the different types of possible glass columns and find out which one is the best to design with.

3 Columns

In this chapter I discuss structural aspect of columns and what kind of shapes are possible to use as a glass column.

3.1 Stability

Stability is the relationship between deformation and load where they are both in equilibrium, which can be defined as stable, neutrally stable and unstable. Stable is if the structure, in this case a glass column, returns to the original tested configuration after disturbance. Unstable is the structure is not possible to move to its original state after disturbance. Finally we have neutrally stable, the structure stops adjusting when the disturbance stops. For the design of the glass column we need to have a state where the deformation and load are equally in balance.

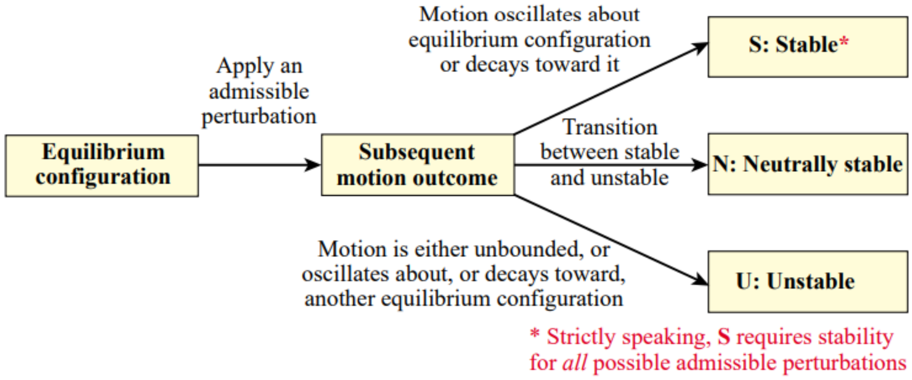


Figure 3.1 Outcomes of stability test done on a static equilibrium configuration.

3.2 Buckling

Buckling is the bending of a column by a force exerted on it (lateral deformation) where the bar shape resembling an arc/wave.
Increasing the force on the column will eventually cause the column to collapse as it begins to bend. A slight increased force in the longitudinal direction, but especially in the transverse direction, is sufficient to cause collapsing. Buckling depends on various factors: the stiffness of a solid material, the length of the column and the resistance to deflection in a (certain) direction.
The general Euler buckling force can be calculated with the following formula:

$$N_{cr} = \frac{\pi^2 * EI}{l_k^2}$$

N_{cr} = Euler buckling force	[N]
E = modulus of elasticity	[N/m^2]
I = moment of inertia of the cross section	[m^4]
l_k = unsupported length of column	[m]

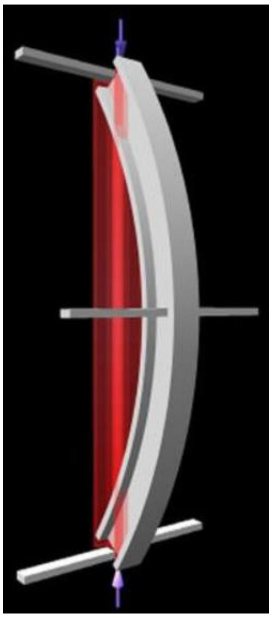


Figure 3.2 Buckling of the red beam.

3.3 Lateral torsional buckling

Lateral torsional buckling happens in an unrestrained beam or column where both ends are unstrained. The member is free to rotate and displace laterally. If an load is applied to the member, twisting and lateral displacement will occur. This results in compression and tension in the beam, where it deflect laterally away from its original position. The difference between lateral torsional buckling and torsion is between the torsional rigidity and the stiffness of the cross section. The vertical axis tries to be not curved while the horizontal planes will rotates. Circle beams are often used against torsional buckling due its shape.
(New Steel Construction, 2006)

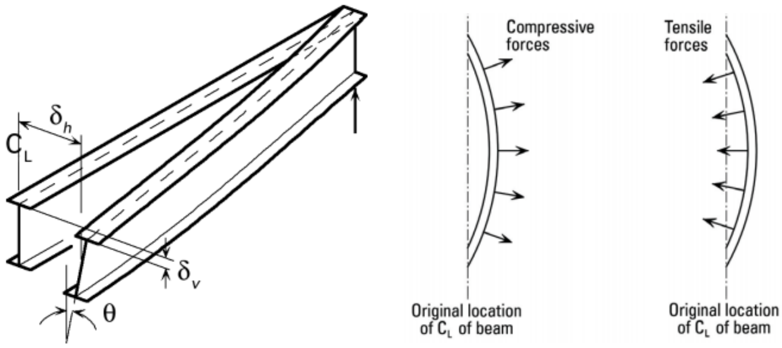


Figure 3.3 *Lateral torsional buckling: lateral displacement and twisting of the beam.*

3.4 Shape and sizing

Glass columns comes in different shapes and sizes. We consider the following six shapes: cylinder, solid glass rods, layered panels (horizontal and vertical), profiled, casted and stacked glass columns. I will examine each of the columns, search for relevant projects and score their strength and weakness based on their properties.

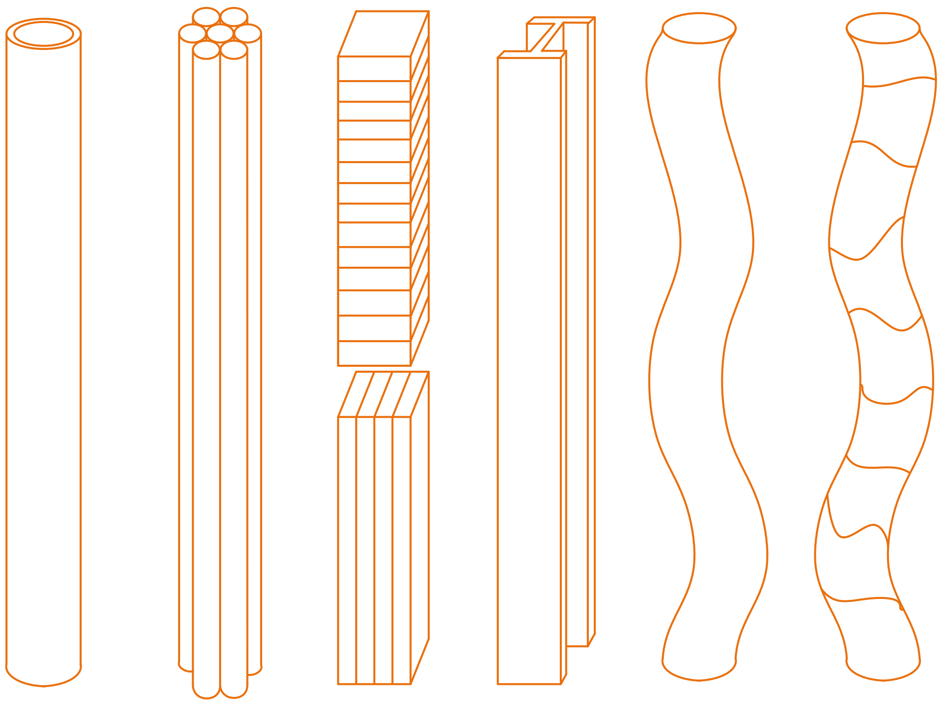


Figure 3.4 *The six columns: cylinder, solid rods, layered, profiled, casted and stacked columns.*

3.4.1 Cylinder

This type of column consist of one glass plate which is curved. The profile is perfectly closed resulting an equal bending stiffness perpendicular to the axial axis of the component.

Project name	Tower Place
Location	London, United Kingdom
Year	2002
Architect	Foster and Partners

The cylinders are used together with the steel cables at the glass panels. The needles is made of a load-bearing inner tube and a protective outer cone. The steel cables adopt all the tensile stresses. There are also steel cables within the cylinder to resist wind suction and connect both ends of the cylinder.

Figure 3.5 The cylinders of Tower Place in London.

Project name	Tensegrity Glass Sculpture
Location	Glasstec 2002 and GlassCon 2003
Year	2002
Architect	Roland Haehnel

Haehnel's work is inspired by sculptures Kenneth Snelson and Buckminster Fuller. His Tensegrity Glass Sculpture is about 6.80 meters high and consists of 12 glass cylinders and 48 steel cables. The cylinders are prestressed with in the inside with steel bars to ensure the compression during manufacturing process. The beginning/ends of the cylinders are finished off with a stainless steel detail connecting the other cylinders.

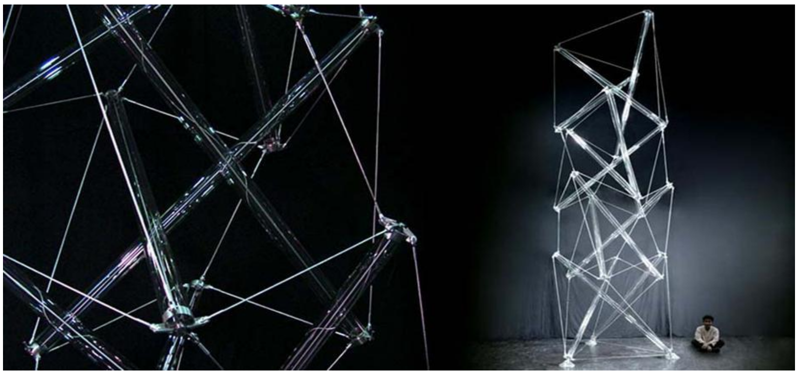


Figure 3.6 Tensegrity Glass Sculpture by Roland Haehnel.

3.4.2 Solid glass rods

Glass columns can also be made with solid glass rods. These rods have a narrow 'small' diameter so they can be easily bundled together to form a large sized column. The rods can be bundled with a resin or welded together.

Project name Swiss Life
Location Haarlem, the Netherlands
Year 1996
Architect Pi de Bruijn

The forces of the solid glass rods are either tensile or compressive in the diagonal length. For this project, steel bars were used for the tensile forces and glass for the compressive forces.

Figure 3.7 Solid glass rods used in Swiss Life.

Project name Developing the bundled glass column
Location Delft, the Netherlands
Year 2015
Architect Faidra Oikonomopoulou

For this project, various types of adhesives, rod configurations and bonding methods are used to find the best equilibrium between structural and visual. This column is made by bonding six solid glass rods together with a transparent UV-curing adhesive. A safety mechanism was made if one of the rods fails, the other rods are capable to carry the total load.

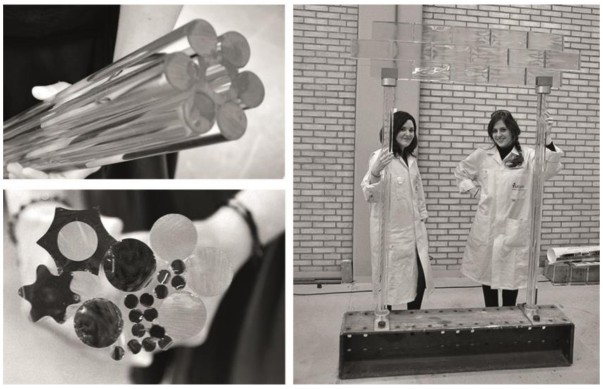


Figure 3.8 Bundles glass columns.

3.4.3 Layered panels

The glass column can be either translucent or transparent, depending in which direction you are looking at. Thick and large layered glass panels often has a greenish-blue tint, this is a result of iron-impurities. True colorless glass can be made with low-iron glass as this is made with very low amounts of iron.

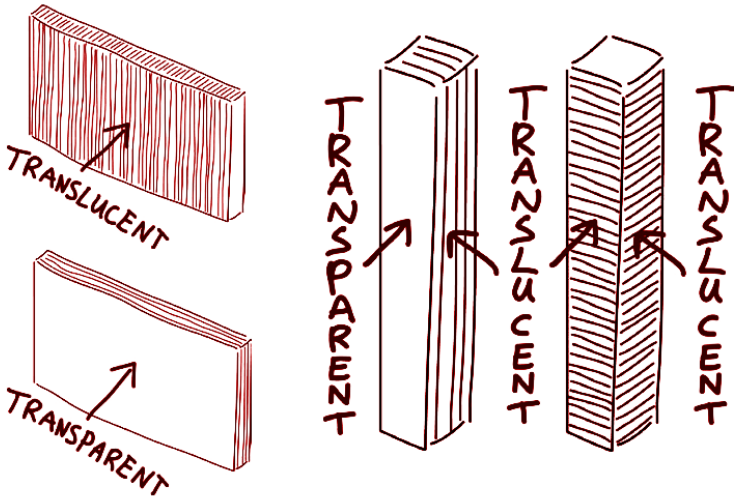


Figure 3.9 The two perspectives of a layered glass column: translucent and transparent.

Project name National Police Memorial
Location London, United Kingdom
Year 2005
Architect Per Arnoldi and Lord Norman Foster

The memorial, location in central London, is made to honor the 4000 police officers killed in the course of their duties. On the right you can see the 550 horizontal layered glass wall which has a total height of 7 meter, 3,1 meter wide and 0,5 meter deep with a total weight of 27.600 kg. The panels are stacked on each other and stabilized by five steel tension rods. The first twenty layers are glued tempered panels.

Figure 3.10 The National Police Memorial.

Project name	Laminata House
Location	Leerdam, the Netherlands
Year	2002
Architect	Gerard Kruunenberg and Paul van der Erve

The basis of the house are vertical laminated glass. The problem for this design was to find a suitable glue which bind the vertical glass, which was developed after an investigation of 5 years. The house consists of 10.000 panels with a silicone-based glue between the panels. Light can come through the glass wall, however the glass does not have its full transparency.

Figure 3.11 Laminata House by Gerard Kruunenberg and Paul van der Erve.

3.4.4 Profiled

These columns consist of multiple flat glass panels and can have many profiles: cruciform, H, U, I, angular, triangular and boxed.

Project name The Danfoss Group
Location Nordborg, Denmark.
Year 2005
Architect schmidt hammer lassen architects
Two rows of cruciform glass columns were placed near the entrance of the reception to support the roof and give transparency to the ground floor.

Figure 3.12 The Danfoss Group.

Project name Glass column
Location Delft, the Netherlands
Year 2011
Architect Eline Ouwerkerk
Five different profiles, squared, double webbed, H, zappi and cruciform, were tested by Ouwerwerk to determine which has the highest resistance to failure. The compressive strength of the H-profile can reach up to 50.8 MPa before failure while choosing the cruciform profile gives a result of 26.0 MPa.

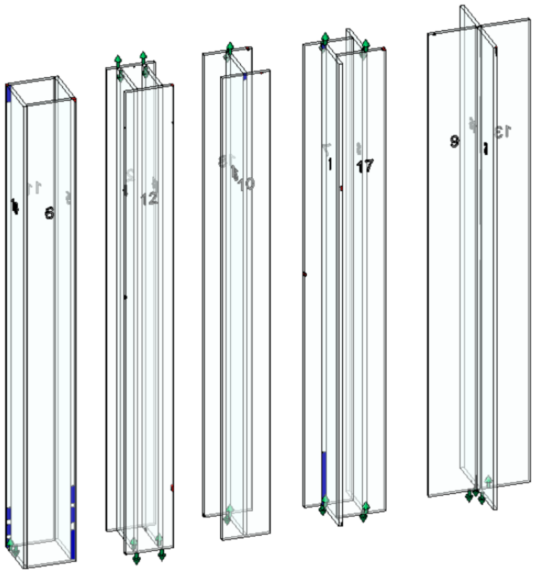


Figure 3.13 Profiled glass columns by Eline Ouwerwerk.

3.4.5 Casted

There are currently no casted column which is used for carrying load of a structure. Experiments with casted column will cost a lot of time as the annealing process depends on the size and volume of the glass. Possibly an idea for a master thesis.
On the right you see a miniature casted glass columns by Armelle Bouchet O'Neill, perhaps a large size possible in the future?

Figure 3.14 Mini casted glass column by Armelle Bouchet O'Neill →

3.4.6 Stacked

Stacked column is less known concept to use as a glass column. Through experiments we know that stacked column has a high compression strength as the loads can be transferred to the center of the glass instead to the edges. Another advantage of this method is the new possibilities for the architect to develop columns, as you can make variations in sizes, shapes, rotations, translations and colors.

Project name	Glass column
Location	Delft, the Netherlands
Year	2016
Architect	Robert Akerboom

Akerboom analyzed the possibilities of using stacked glass to replace two 6 meter high concrete columns in the Berlage Zaal. 54 small bricks will be stacked by using a interlocking connection like Lego as you can easily disassemble the bricks and reuse it. The end connection is a mix between a clamp and a hinge. A general safety factor for glass does not exist, therefore a factor of 4 was taken. Small bubbles was seen on the bricks which decreased the overall strength of the structure, however it could be solved by using a higher temperature to let the air out during manufacturing. The eccentricity can also vary as the bricks are stacked on top of each other, impacting the whole strength of the column.

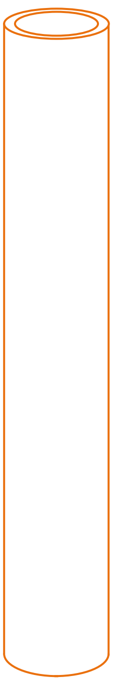
Figure 3.15 Casted column in the Berlage Zaal by Robert Akerboom

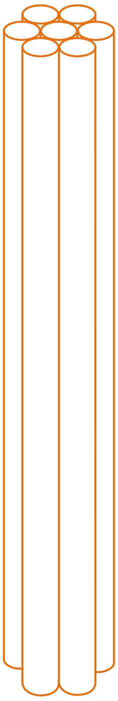
3.5 Analyze

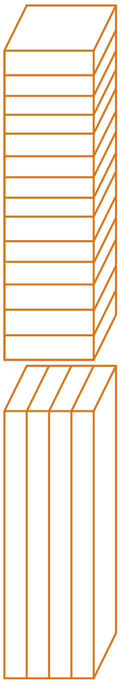
The columns will scored on eight criteria with points given between 0,0 and 5,0 (the higher the better):

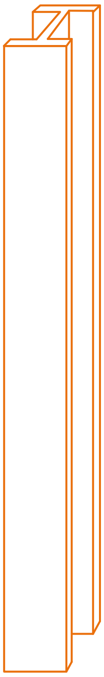
Criteria	%	Description	Scoring
Shape	5	How elegant is the glass column that blends in the architectural language of the construction?	Does not blend ←→ blends well
Size	12.5	What are the dimensional restrictions of the glass column?	Low height ←→ high height
Manufacturing time	12.5	How long does it take to manufacture the whole glass column?	Much time ←→ little time
Manufacturing cost	10	How are the relative costs for the glass column?	High cost ←→ low cost
Assembly	10	How difficult is it to make the glass column?	Difficult ←→ easy
Connections	12.5	How structural and aesthetically pleasing are the connecting components for the glass column?	Limited variation ←→ great variation
Transparency	17.5	How transparent is the column?	Not transparent ←→ transparent
Safety	20	How is the safety of the glass column when it fails?	Unsafe ←→ safe

Table 3.1 Score matrix system for the columns.

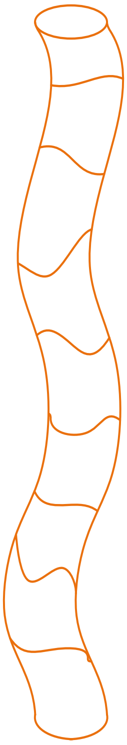
Cylinder	**Criteria**	**Explanation**	**Score**
	Shape	Very simplistic.	1.5
	Size	Can have a large diameter size of 500 cm.	5.0
	Manufacturing time	Often requires layering, but the form is not time consuming to make.	3.5
	Manufacturing cost	Only curved glass and adhesive glue are needed, therefore 'cheap'.	3.5
	Assembly	The glass needs to be curved, this takes an extra process	3.5
	Connections	A wide offer of connections can be made with the column.	4.0
	Transparency	Very transparent as it has no edges and no distortions.	5.0
	Safety	Can be increased by layering.	3.0

Rods	Criteria	Explanation	Score
	Shape	Offers a range of variety.	3.0
	Size	The height maximum depends on the amount of rods	4.0
	Manufacturing time	Need to manufacture multiple rods	2.0
	Manufacturing cost	Need more volume as you need multiple rods	1.5
	Assembly	Can easily be glued together	4.5
	Connections	A wide offer of connections can be made with the column.	4.0
	Transparency	It can be transparent, but not visible enough. Depends on the amount of rods	2.5
	Safety	Other rods can take care of the load if one of them fail	4.5

Layered	Criteria	Explanation	Score
	Shape	Can rotate the plates to give it a more dynamic vibe	4.0
	Size	Layered columns can go up to 17 meters height.	5.0
	Manufacturing time	It can take up hundreds to thousands of plates to manufacture a few glass layered column and don't forget about cutting them all, gluing and drying.	1.0
	Manufacturing cost	It can take up hundreds to thousands of plates to manufacture a few glass layered column.	0.5
	Assembly	Easy to make, but difficult to replace a horizontal plate if it is broken.	2.0
	Connections	A limited offer of connections can be made with the column.	2.5
	Transparency	Depends on the direction you are looking at, but the transparency is very limited	0.5
	Safety	The layered glass column can carry high amount of load. By failure of one plate, adjacent plates will carry the load.	5.0

Profiled	Criteria	Explanation	Score
	Shape	Has lots of configurations.	3.0
	Size	Profiled columns can go up to 17 meters height..	5.0
	Manufacturing time	Common and standard size.	4.5
	Manufacturing cost	Common and standard size, easy to mass produce.	4.0
	Assembly	Only needs to be glued.	4.0
	Connections	A wide offer of connections can be made with the column.	4.0
	Transparency	Depends on the configuration.	3.5
	Safety	The other plates can carry on the load if on them breaks.	3.0

Casted	Criteria	Explanation	Score
	Shape	Possibility are endless, theoretically.	5.0
	Size	Possibility are endless, theoretically.	5.0
	Manufacturing time	Can take up to a few months to years for a single column.	0.0
	Manufacturing cost	Specially designed molds need to be made and lots of melted glass needed.	0.5
	Assembly	Only need to pour the hot melted glass into the mold.	4.5
	Connections	Depends on the form.	2.5
	Transparency	Depends on the form as rounds shapes guarantee a full transparency.	4.5
	Safety	No safety mechanism can be implemented as this hinders the transparency.	0.0

Stacked	Criteria	Explanation	Score
	Shape	Great amount of configuration possible	4.5
	Size	Depends on the circumference.	4.5
	Manufacturing time	By making small bricks you speed the process instead of one long casted column.	4.0
	Manufacturing cost	Need to make multiple molds to speed up the manufacturing process. These molds can be reused.	2.5
	Assembly	Only need to pour the hot melted glass into the mold.	4.5
	Connections	A wide offer of connections can be made with the column.	4.0
	Transparency	Too many small stacked bricks can also decrease the transparency	4.5
	Safety	Can use liquid adhesive interlayer to bond the glass, preventing shards flying out of the stacked glass column.	3.5

3.6 Conclusion

Criteria	%	Cylinder	Rods	Layered	Profiled	Casted	Stacked
Shape	5	1.5	3	4	3	5	4.5
Size	12.5	5	4	5	5	5	4.5
Manufacturing time	12.5	3.5	2	1	4.5	0	4
Manufacturing cost	10	3.5	1.5	0.5	4	0.5	2.5
Assembly	10	4	4.5	2	4	4.5	4.5
Connections	12.5	4	4	2.5	4	2.5	4
Transparency	17.5	5	2.5	0.5	3.5	4.5	4.5
Safety	20	3	4.5	5	3	0	3.5
Score		3.863	3.338	2.6	3.85	2.48	3.975

Table 3.2 The scores of all glass columns based on the criteria.

The stacked column scored overall the best by showing great scores aesthetically and structural. The variations in shapes and sizes not only gives the engineer some tools the play, but also for the architect. The assembling is an easy process as you only need to stack the glass parts on top of each other and add an adhesive glue. Transparency can be obtained due cast glass parts.

In the next chapter I will continue my research with the stacked column as the foundation for my designs.

4. Design phase

In this chapter I use the knowledge that I gained the past 3 chapters to design a few glass column concepts. Originally, I had three different concepts that needed extra elaboration. My supervisors advised me to focus on two, due time constraints. The two designs are the stem and the Tetris design.

4.1 Design 1 – Stem

Inspiration

The stem of a plant holds all the other parts which are attached. It provides a powerful cylindrical structure and reinforces the fruits, leaves, flowers and connects them with the roots. Looking at the cross section of the right figure, we can see a stem cross-section of a flax. The inner part of the stem holds the outer parts, which are made of small rods/cylindrical structures. If one section of the outer parts fail, the other components will still carry on the load.

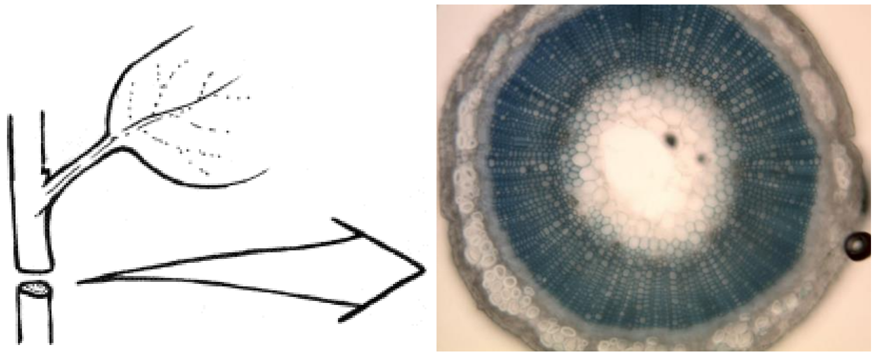


Figure 4.1 Cross-section of the flax.

This inspiration has been used for my first design. The only suitable method to manufacture this design is casted glass. I did not want to make a circular column as I found it too general, instead I used an elliptical shape. The surface is divided into six parts. One part has two pins and the other part has two matching holes where the components can interlock with each other. This happens alternately to evenly distribute the load. The inner part where the stem supposed to be has been left out due to saving volume, time and money.

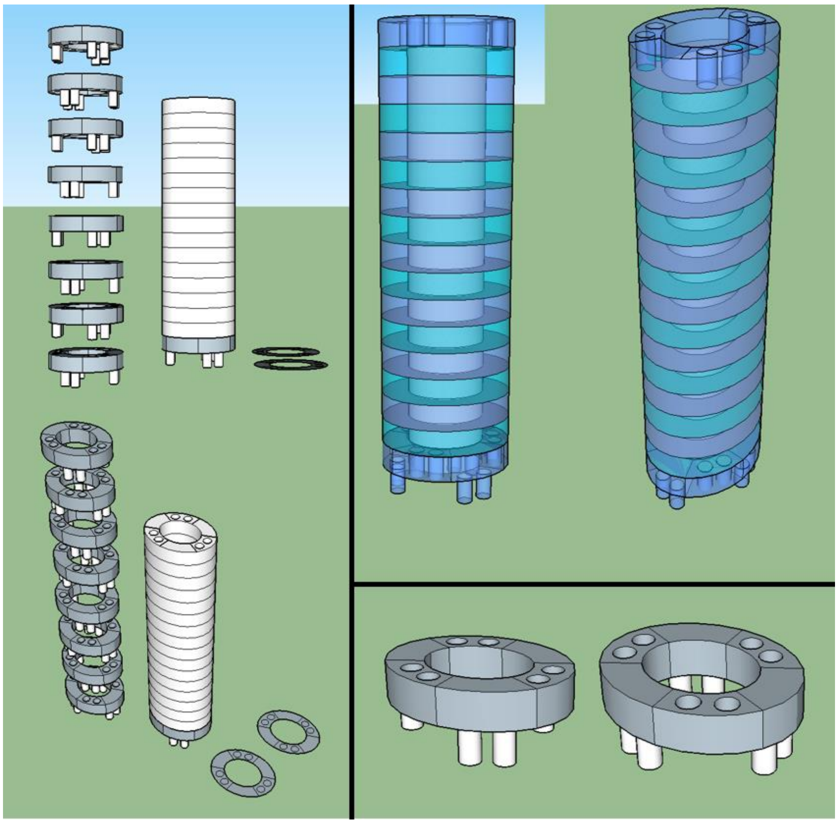


Figure 4.2 Left side: the interlocking system in action. Right bottom corner: the two different components (mirrored). Left upper corner: the final design with two different color of glass.

4.2 Design 2 – Tetris

Inspiration

As a little kid I used to watch my mom play video games, especially on the Game Boy. A nice short animation of a rocket launching to the moon is shown when you have finished the game. The size of the rocket becomes larger and larger as it depends on your total points. I occasionally play Tetris as it is still very fun and reminds me of my childhood, watching those blocks falling down and stacking them. This has brought me of the idea of using them for my glass column design. Instead of using all the different shapes, I am planning to just use one shape as this will be more efficient.

Figure 4.3 Tetris blocks falling down, covert art from the NES (1984).

This design is based on the traditional S/Z-shape of Tetris. I added an extra block in the middle to create a void, which gives a more dynamic feel to it. This expression is intensified by rotating and stacking the shape as seen in the figure below. Using different colors I think it can give a more beautiful vibe to the column. Also, I will research the possibility of using cast glass as well as laminated glass.

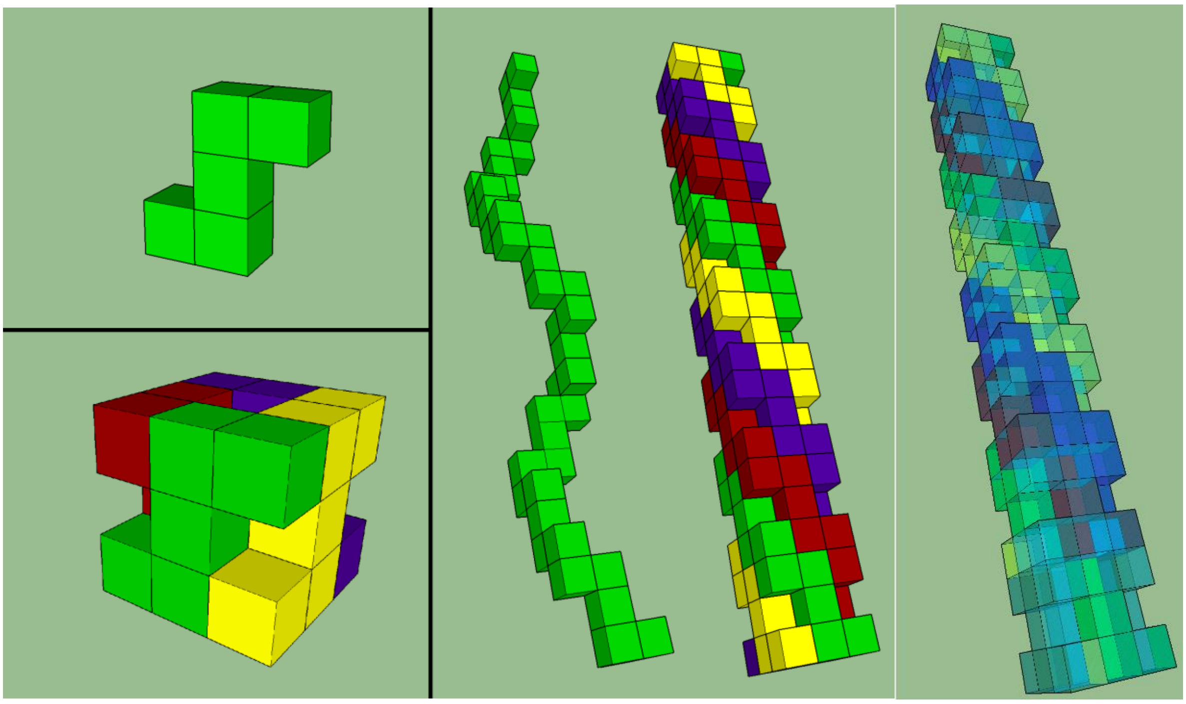


Figure 4.4 Left upper corner: modified Tetris shape used for this design. Left lower corner: four different shape interlocked with each other. Right side: The stacking of the modified Tetris shape.

4.3 Selection criteria

My initial idea was to use the casting method to manufacture the Tetris shape, however after feedback of my supervisors they advised me to experiment the possibility of using laminated glass as well. I also added the buckling load as a criteria (just for this chapter), based on their feedback

In this selection I will score the following three designs: stem, Tetris (casted) and Tetris (laminated). Each design will be scored on nine criteria with points given between 0,0 and 5,0 (higher is better) to determine which design is the best.

Criteria	%	Description		
Shape	5	How elegant is the glass column that blends in the architectural language of the construction?		
		Scoring: does not blend	←→	blends well
Sizing	10	How much area is needed for the glass component?		
		Scoring: little	←→	much
Manufacturing time	12,5	How long does it take to manufacture the glass component?		
		Scoring: much time	←→	little time
Manufacturing cost	7,5	How are the relative costs for the glass column?		
		Scoring: high cost	←→	low cost
Assembly	7,5	How difficult is it to make the glass component (make ability)?		
		Scoring: difficult	←→	easy
Connection	10	How structural and aesthetically pleasing are the connecting components for the glass column with each other, the foundation and the top?		
		Scoring: limited variation	←→	great variation
Transparency	12,5	How transparent is the column?		
		Scoring: not transparent	←→	transparent
Safety	20	How is the safety of the glass column when it fails?		
		Scoring: unsafe	←→	safe
Buckling load	15	How much load can the glass column endure before failing?		
		Scoring: little	←→	much

Table 4.1 Score matrix system for the designs.

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4.3.1 Design 1 – Stem

Shape

The form is simplistic, but also distinctive thanks to its elliptical shape. Different variations for this design is not possible as the components can only stack up on each other.

Sizing

An elliptical area is needed for this design. Volume is saved by not filling up the center part, as the rest of the component can still carry on the load. It must be taken into account that there are also pins at the bottom of the component which makes the height of the component twice as long.

Manufacturing time

Not all parts of the component will be annealed at the same rate due to its elliptical shape and the protruding pins. Two different molds needs to be made and during the manufacturing process the amount of casted glass must be equal to its mirrored component. The cooldown time is the same for both of them.

Manufacturing cost

The cost is relatively high due to its high manufacturing time and the requirement of having to manufacture two different components.

Assembly

Producing the components is not too difficult as you need to pour hot glass into the mold. Extra attention to the pins should be given as these are the weakest part of the component.

Connection

The connection between the components fits perfectly by using the pins, also adding an adhesive between each layer will strengthen it. For the ends of the column, metal 'shoes' are suggested as this can assure a smooth change of load from the end connection to the casted glass. This consist of a steel ending with a copper interlayer.(Akerboom R, 2016)


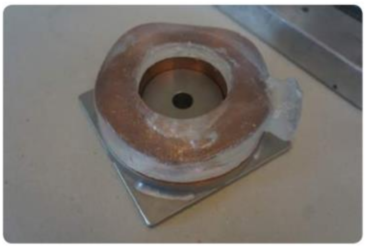

Figure 4.5 The steel endings and the copper interlayer

Transparency

Very transparent as there are no edges which can reduce the transparency

Safety

Can use (liquid) adhesive to bond the glass and pins, preventing shards flying out of the stacked glass column. If one pin is damaged, the other five pins can carry on the load.

Buckling load

The design has a relatively high slenderness which is susceptible for buckling. The pins blocks the possible rotational buckling load. A strong (liquid) adhesive can form a secure bond between the components which endure more bucking load.

4.3.2 Design 2a– Tetris (casted)

Shape

There are many configuration possible as you can easily turn and rotate the shape.

Sizing

A squared area is needed for this design by interlocking 4 modified Tetris shapes. The same method as design 1 is applied as the center is not filled up as the rest of the modified Tetris shapes can carry on the load.

Manufacturing time

Using square shapes is a hassle as the annealing process for the corners is not equally to the radius of the modified Tetris shape. Time will be saved compared to design 1 as you only need one shape for the glass column.

Manufacturing cost

You only need one mold to use get the modified Tetris shape. The costs are therefore low.

Assembly

Suggested is to place the mold sideways as this is a more efficient way of cooling down compared to the mold staying up. Hot liquid glass is then poured into the mold.

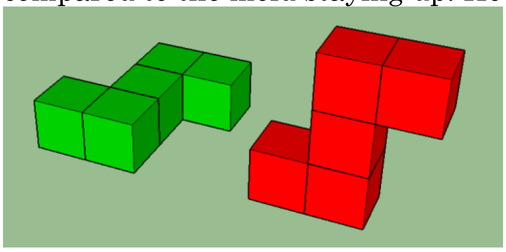

Figure 4.6 Preferred position for the manufacturing process by placing it like the green modified Tetris shape.

Connection

The connection to the other shapes will be done by using an adhesive interlayer. Mechanical connections between the shapes is not preferred as this lowers the transparency and the elegancy.

Transparency

The edges (of the cubes) reduces the transparency of the column.

Safety

If one of the smaller cubes of the modified Tetris shape cracks or is destroyed, the other cubes can still carry on the rest of the load.

Buckling load

The same method can be used here as design 1 where using a (liquid) adhesive strengthen the bonds of the shapes. This design is probably prone for buckling as the slenderness is high. Rotational buckling is also possible as the shapes are glued together with an adhesive. There are no pins available, as design 1, which can block the rotation.

4.3.3 Design 2b– Tetris (laminated)

Some of the description are the same as the casted version, the only difference is the method used for producing the modified Tetris shape, lamented.

Shape

There are many configuration possible as you can easily turn and rotate the shape.

Sizing

A squared area is needed for this design by interlocking 4 modified Tetris shapes. The same method as design 1 is applied as the center is not filled up as the rest of the modified Tetris shapes can carry on the load.

Manufacturing time

Extra time is needed because the shape is not common or standardized, also it needs to be specially cut to the modified Tetris shape and glued together.

Manufacturing cost

The costs are high due to modification of the plates and a high amount are needed to get the modified Tetris shape.

Assembly

Much faster and time efficient compared to design 2a. You only need to glued the plates together after it has been cut to the desired shape.

Connection

The laminated Tetris shape are glued together with an adhesive. A modified clamped mechanism can be used to connect the cube to the top and bottom the column

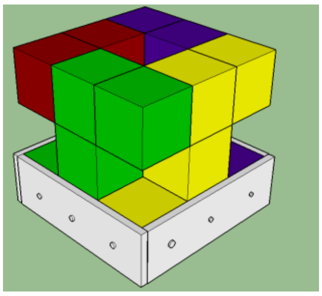

Figure 4.7 Clamped connection of four interlocked modified Tetris shape

Transparency

It depends on the direction which you are looking at as this can be transparent or translucent. The overall transparency is much less compared to design 1 and 2a.

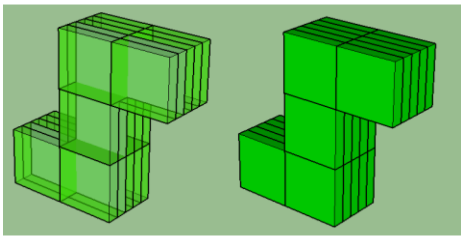

Figure 4.8 Example of vertical laminated modified Tetris shape (as glass and as a non-transparent material)

Safety

The layered glass column can carry high amount of load. By failure of one plate, adjacent plates will carry the load.

Buckling load

Horizontally laminated plates are better for distributing the load than vertically ones. Horizontal layering produces a much stronger shape to carry on the buckling load. Rotational buckling is also possible as the shapes are glued together with an adhesive.

4.4 Conclusion

Criteria	%	Design 1	Design 2a	Design 2b
Shape	5	4	4.5	4.5
Sizing	10	4	4.5	4.5
Manufacturing time	12.5	0.5	1	1.5
Manufacturing cost	7.5	1.5	1.5	2
Assembly	7.5	4.5	4.5	4
Connection	10	3.5	3.5	4.5
Transparency	12.5	4.5	4.5	1
Safety	20	3.5	3.5	4.5
Buckling load	15	4	3.5	4.5
Total score		3.325	3.3875	3.4625

Table 4.2 The final scores of the 3 designs.

It is overall a very close call between each design. However, based on the scores I choose design 2b as my design which I will work for my research. In the next chapter I will start doing research on my case study.

5. Case study

Figure 5.1 Civil Engineering at Delft

I wanted to bring a personal touch for my thesis and therefore chose the Civil Engineering faculty at the University of Technology in Delft as my case study. This is the university where I am currently doing my bachelor. The columns which needed to be replaced are represented in the figure below.

Figure 5.2 The concrete columns of the Civil Engineering faculty

The blueprints/maps can be found in the appendix. The 60 columns which will be replaced are on the first floor on the faculty. This will bring some fresh air to the building as these columns have not changed in more than 40 years. (Máčel, 1994)

5.1 Dimensions

The dimensions of the columns are 4920 x 400 x 440 mm (height, width, length). More details can be found in the appendix.

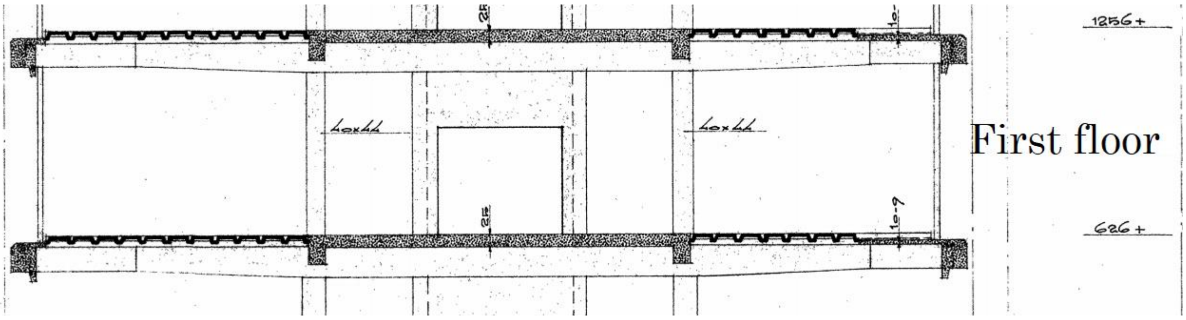

Figure 5.3 Cross-section of the first floor

5.2 General loads

Before the design of the column can start we need to look at different aspects, such as the idea of the structure, possible functions, usage and loads. The last one is the most important as this determines the dimensions of the column design. Two variation of loads are addressed: permanent and variable.

5.2.1 Permanent load

First I calculated the permanent load of each floor of the faculty for all different materials. The average load for each floor is 2,76 kN/m^2.
(Public.Resource.Org, 2012) (Quick Reference, 2015)

Permanent, # floor [kN/m²]	Second floor	Third floor	Fourth floor	Fifth floor
insulation	0,1	0,1	0,1	0,1
concrete slab, 250 mm	5,9	5,9	5,9	5,9
wall, concrete aggregate 155 mm	0,092	0,092	0,092	0,092
installations	0,3	0,3	0,3	0,3
roof tiles + underlay and purlins				0,65
roof surface, objects installations				1,33
Total permanent # floor	6,392	6,392	6,392	8,372
Total permanent floor, average	6,887			

Permanent, load [kN]	Loadcase [kN/m2]	Area [m2]	Floors [#]	Load [kN]
total permanent floor, average	6,887	51,84	4	1428,088
Total permanent load				1428,088

Table 5.1 Data on the permanent load.

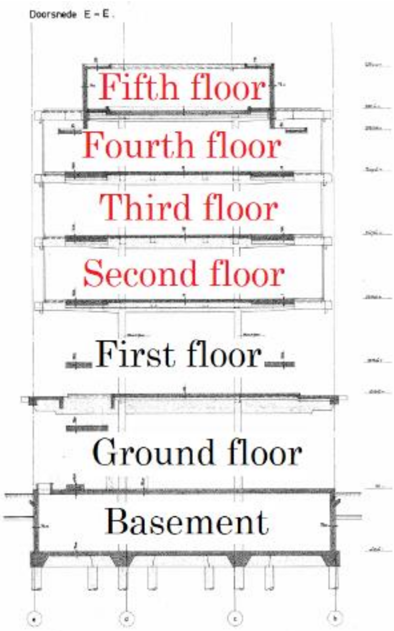

Figure 5.4 Cross-section of building and the floors

The total permanent load is 1428 kN.

5.2.2 Variable load

This load various during the day. I used the Quick Reference to get the variable load of school (C1). Then I calculated the function of each floor which is only 'office use'. The area that I used was 7200 x 7200 mm, but for the office I used 7200 x 3600 mm because the other half is a hallway.

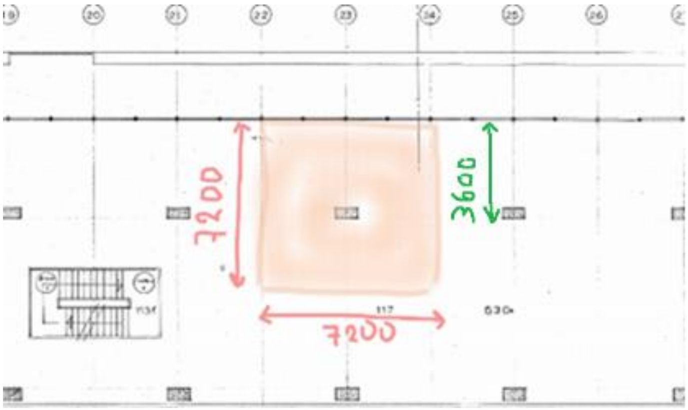

Figure 5.5 Effective area of the concrete column.

Variable, load [kN]	Loadcase [kN/m2]	Area [m2]	Floors [#]	Load [kN]
school (C1)	4	51,84	4	829,44
Office use	2,4	25,92	3	186,624
Total variable load				1016,064

Table 5.2 Data on the variable load.

The total variable load is 1016 kN.

5.3 Safety factor

To get the total load, we need to sum of the permanent and variable load. 1428 + 1016 ≈ 2444 kN.
Finally we need to multiply our total load with a safety factor. A factor of 4 is suggested. 2444 x 4 = 9776 kN = 9,78 MN.

The total load on floor 1 for the columns are 9,78 MN.

5.4 Buckling force

I used the following formula to calculate the buckling force:

$$N_{cr} = \frac{\pi^2 * EI}{l_k^2}$$

For the modulus of elasticity (E) of glass I used 70.000 N/mm^2, because I think that is a decent average. The moment of inertia (I) depends on the area of the cross section. To make things easy, I used the top of the modified Tetris shape which looked as a square tube.

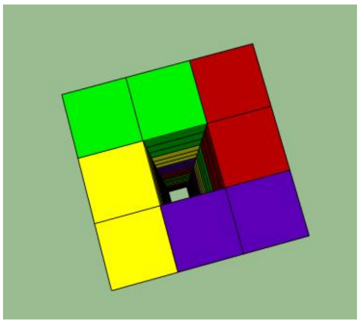

Figure 5.6 Square tube position of the modified Tetris shape.

The lengths are 750 x 750 mm. Each individual cube has a length of 250 mm.
To calculate the moment of inertia, the following formula was used:

$$I_x = \frac{bh^3 - (b-2w)(h-2w)^3}{12}$$

The values for the letters are b = 750 mm, h = 750 mm and w = 250 mm. The moment of inertia is 2.6042 E^{10} mm^4

The final data we need is the length of the column, which is 4920 mm. Now we can calculate the buckling force of the column.

$$N_{cr} = \frac{\pi^2 * EI}{l_k^2} = \frac{\pi^2 * 70.000 * 2.6042E10}{4920^2} = 743{,}26\ MN$$

But the column is not fully massive due the voids at some corners. Therefor I propose to reduce the buckling force by 65% (better safe than sorry). This leads to a buckling force of 483,12 MN (743,26 x 0,65).

$$N_{cr}\ (483{,}12\ MN) > Total\ load\ (9{,}78\ MN)$$

5.5 Conclusion

It is hard to tell how much load the glass column can carry in practice as this is all theoretical. I found it very challenging to calculate the buckling force of glass in comparison to steel, concrete or even wooden columns as there are guidelines (Eurocode) on how to calculate all aspects. Countless experiments are done for those material to get some factual numbers. However, this is not the case with glass. Everything is still uncertain. Tons of analysis and tests have been performed for glass but that is still not enough to get a general formula to calculate with glass as material. Even by a safety factor of 4 we still cannot be sure enough of the safety. According to what I have calculated, my design probably will not fail when used in reality.

For the next and final chapter I will design the Tetris column based on the results, data, information and calculations of earlier chapters.

6. Definitive column design

In this final chapter I will design the Tetris column with laminated pieces and answering the seven sub-goals. In the end a conclusion and recommendation is given.

6.1 Shape

The original Tetris blocks come in seven different shapes. The shape I used is based on the S-shape of Tetris. An extra block is added to the middle to create a more unique shape.

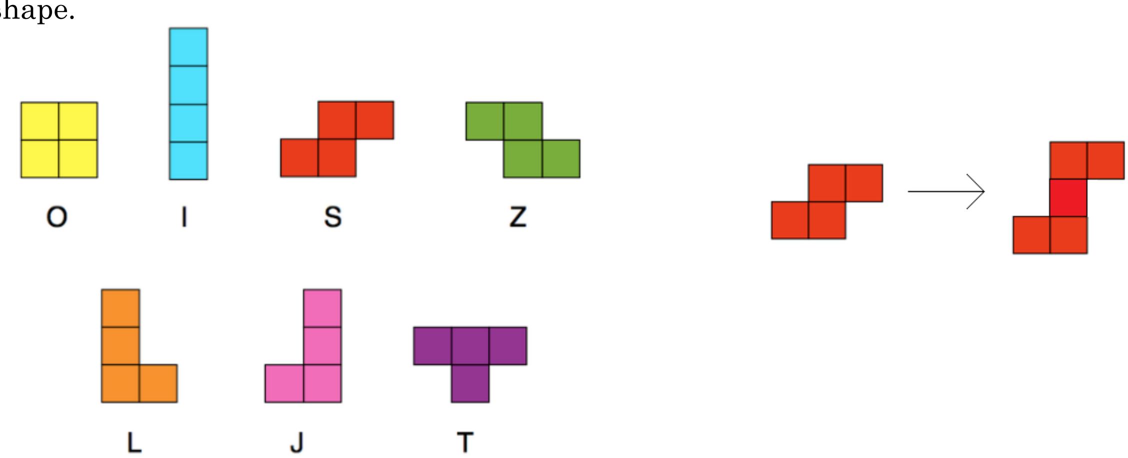

Figure 6.1 The original 7 Tetris shapes (left). The modified Tetris shape (right).

Four colors used for the modified Tetris shapes are red, green, cyan and yellow. The basic shape of the column consist of these four colors.

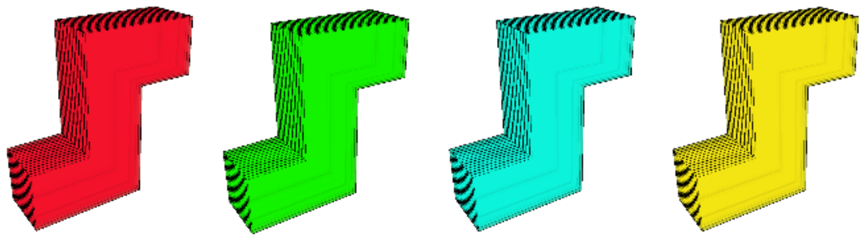

Figure 6.2 The four colors used for the Tetris column. Red, lime, cyan and yellow.

The laminated Tetris pieces are rotated and shifted together creating one single composed cubical Tetris as shown at the figure below. This cube will be the foundation of my glass column design.

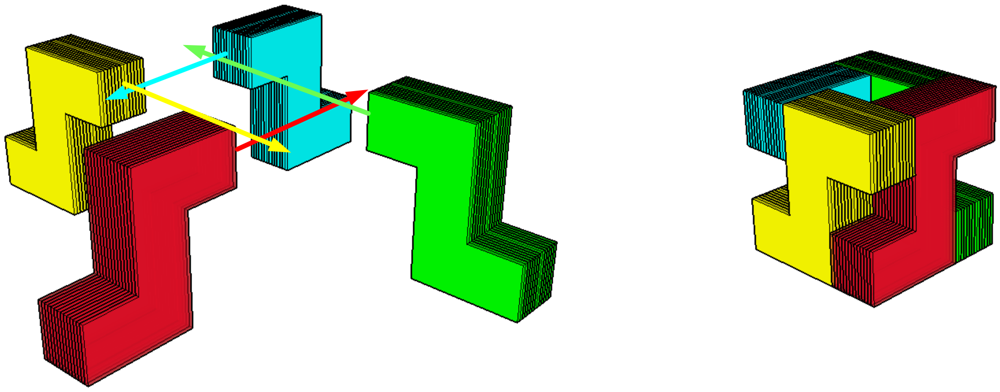

Figure 6.3 Shifting the four laminated pieces together to the cubical Tetris.

The cubical Tetris are stacked above upon each other with each cube rotated 90 degrees counterclockwise. A colored snake pattern can be seen of the column which creates a very dynamic movement while being static. There are voids at some of the corners creating a space where, for example, students can temporary put their hot cups on it while having a conversation. The bottom part of the glass column is protected with a steel plate and the top of the column is has a block of high-strength concrete which connects to the top of the floor, both of this will explained at section DETAIL of the report.

The elegance of glass column blends it well with its environment and gives a happier and lively vibe to the first floor as opposed of the grey, bleak concrete columns.

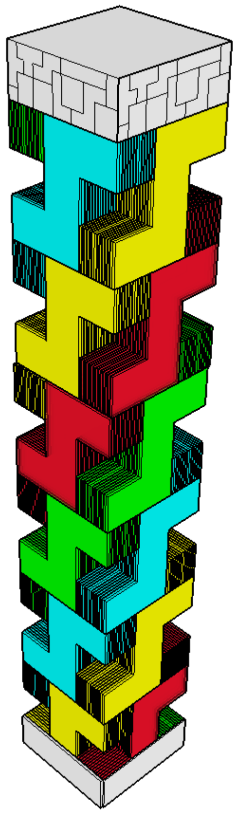

Figure 6.4 The laminated Tetris column. →

6.2 Sizing

The height of one modified Tetris shape is 750 mm with a total length of 750 mm and a width of 250 mm. 14 laminated glass slices are put together to get one single Tetris piece. The dimensions are given at figure below.

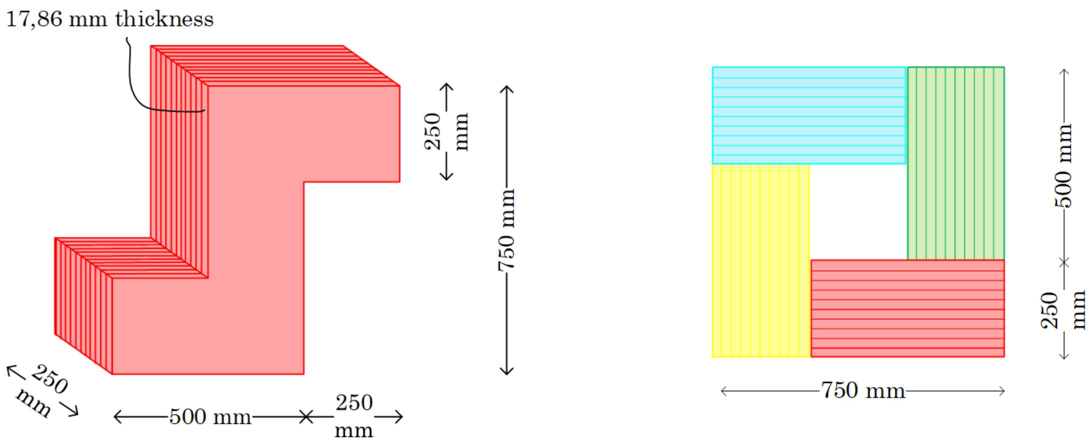

Figure 6.5 The dimensions of the modified Tetris shape.

An area of 562.500 mm^2 (750 x 750 mm) is needed for one cubical Tetris. The height of one cubic Tetris is 750 mm. Six of these are stacked above each other resulting a height of 4500 mm (6 x 750 mm). The remaining gap will be filled with high-strength to make it fit perfectly with the bottom of the 2nd floor.

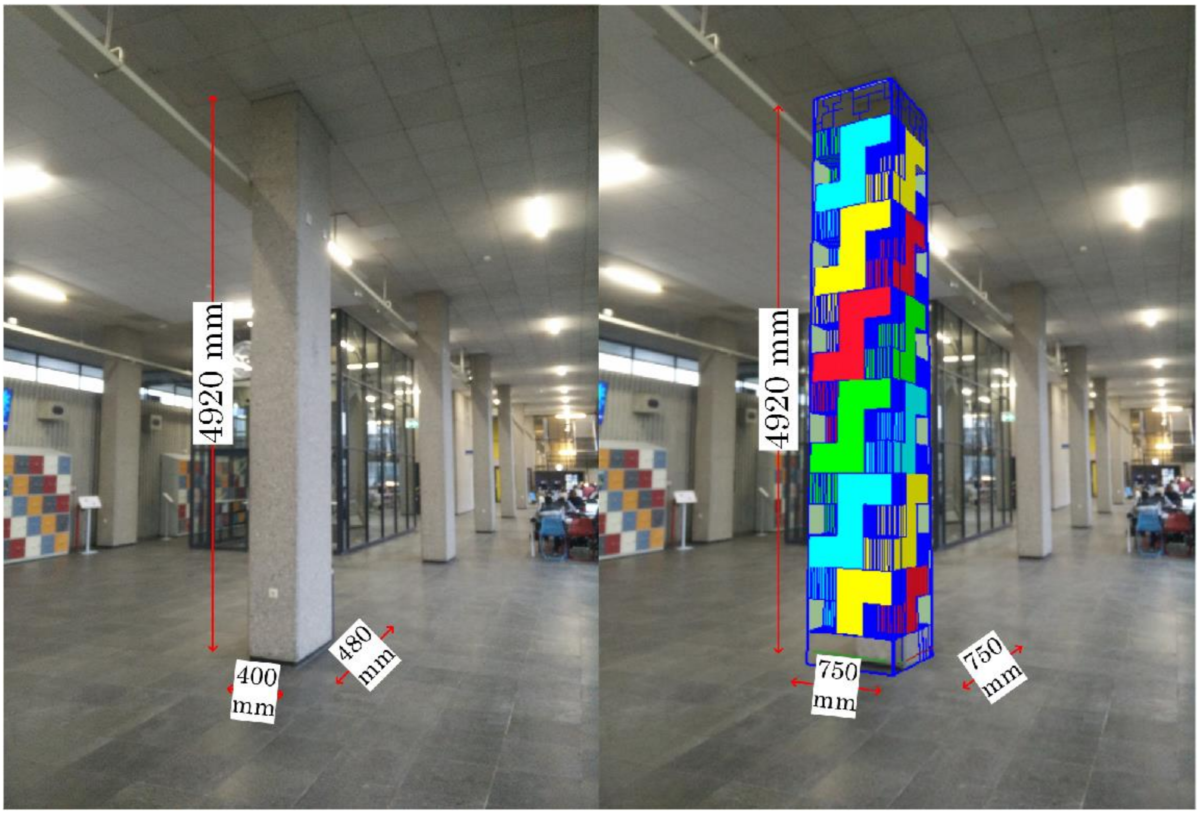

Figure 6.6 The existing concrete column (left) and the laminated Tetris column (right) with their dimensions).

6.3 Manufacturing

The production of the modified Tetris shapes takes place in a factory that produces float glass. One company I found that specialize in custom cutting colored laminated glass was FAB Glass and Mirror which. They use color polyvinyl butyral (PVB) as interlayers between the laminated glass. Different dimensions of laminated glass can be produced in the factory. I chose one of the standard sizes which has a length of 2641,6 mm, width of 1778 mm and a thickness of 17,86 mm.

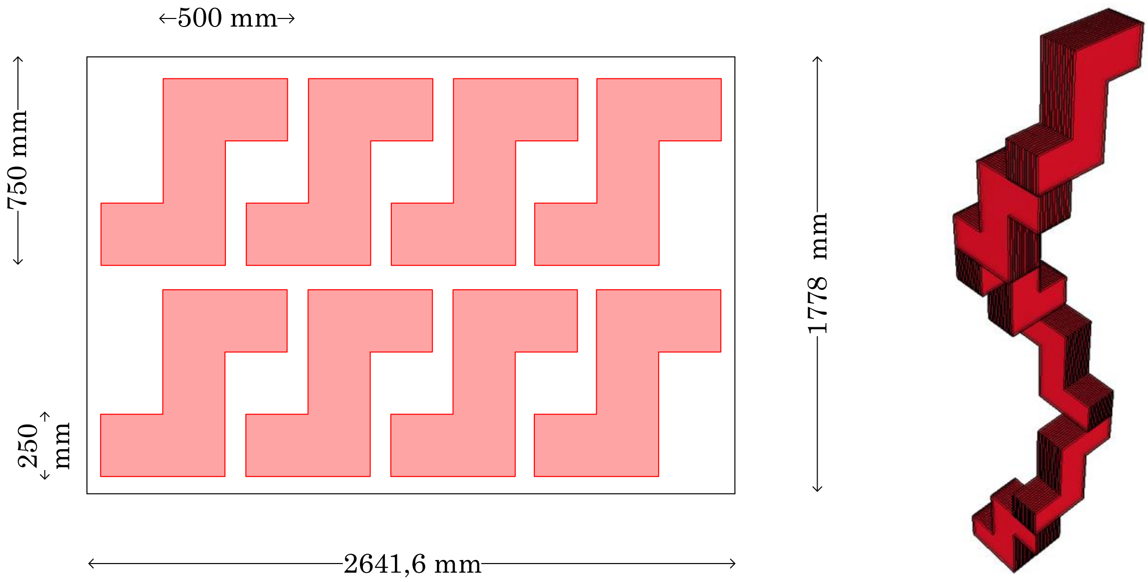

Figure 6.7 Dimensions of the sheet from FAB Glass and Mirror (left) and 6 stacked Tetris shapes (right)

One sheet with these dimensions can produce eight slices of the modified Tetris shape. A total of 84 slices (6 Tetris x 14 slices) is needed to manufacture one colored modified Tetris shape to build one glass column.

11 (10,5 to be exact) sheets of one color is needed and we use four colors, therefor the total sheets needed for one glass column is 44 sheets. The price of one colored sheet (tempered, flat polished) laminated glass costs €4953 ($6043,86). We need to multiply that amount by 44 sheets. The price of just the glass elements of the column will cost a total of €217.932. The concrete column at the faculty cost around €1150 (BCG Concrete, 2017)

The weight of one colored sheet is 223 kg (491,9 lbs). As we need 44 sheets for the column, the total weight of the glass elements of the column will be 9812 kg.
The existing concrete columns has a weight of 2164,8 kg (4,4 x 0,4 x 0,44 x 2500). If we compare the difference of the two columns, the glass column weights 4,53 times more than the concrete column.

The manufacturing time will be around one month per sheet after ordering.

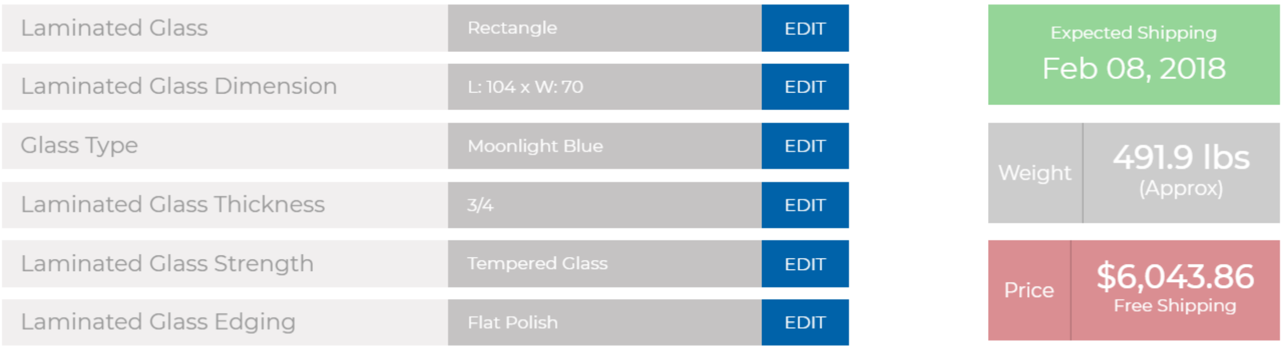

Figure 6.8 Summary of my order at FAB Glass and Mirror.

6.4 Assembly

Here I will discuss what the procedures are for replacing and installing the glass column. The first thing to do is to remove the existing concrete column and clear the area for safety measurements. This can be done by placing two temporary columns near the concrete column. Underneath the temporary columns we place a jacking system and slowly lift them up. The weight of the of floor is now shifted from the existed concrete column to both of the temporary columns. Now we can safely remove the concrete column.

The next step is start polishing the ground and top of the first floor to flat the surface. Before placing the first Tetris parts we need to install the detail of the bottom (further explanation is given at the DETAIL section). A vertical steel plate of 250 mm is placed at the bottom against the Tetris shape, this is to prevent any direct damage to the column as people can walk or kick against the bottom. A layer of neoprene is filled between the glass and steel parts to avoid direct contact with both materials.

Now we can build up the glass column. This begins by placing four Tetris shapes to make a cube. The four colors helps greatly as you can see immediately where to place the Tetris parts. Before stacking up the next part it is optional to put a thin layer of polyurethane of 2 mm at the top of each Tetris section, which is capable of taking high load. There are a different hardness of polyurethane, which dictates the compression stresses.

There is a gap of approximately 460 mm after stacking all the Tetris cubes till the glass column reaches the top part of the floor. This cannot be filled with a Tetris shape, as there are no pieces with that specific height. A solution for this is to place a cubical mold on top of the glass column and inject that with high-strength concrete. We now need to wait till it is hardened enough so it can carry the load of the floor. It is highly recommended to place polyurethane between the glass design and high-strength concrete.

The last step is to slowly lifting down the jacking system of both temporary columns. The floor will transport the load from the two columns to the glass column. We can now safely remove the temporary columns.

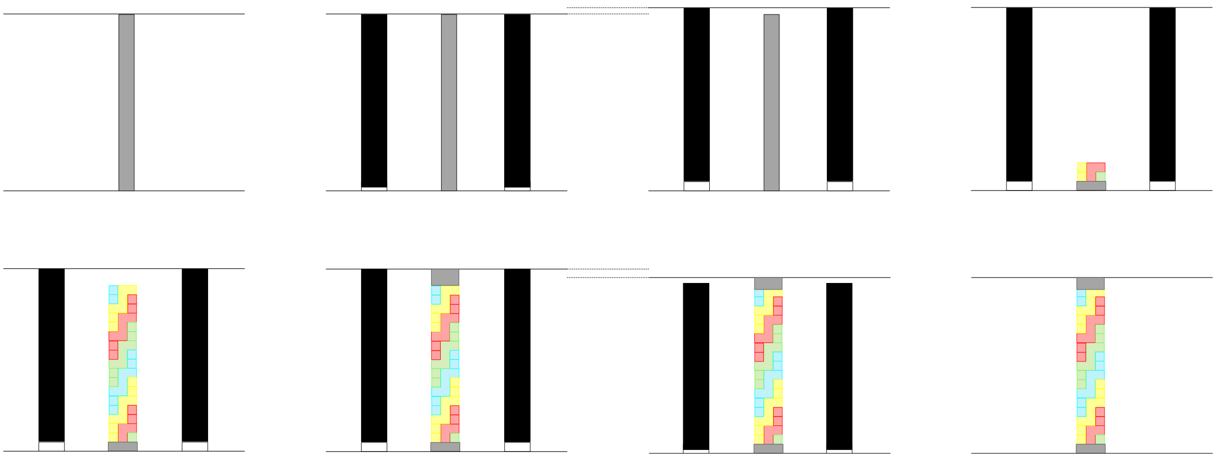

Figure 6.9 Assembly of the laminated Tetris column in 8 steps starting from left-above and going clockwise.

6.5 Connections and detail

The connection between the top and the bottom of the glass column to the floor will be described in this part. The details are also given.

Top

After stacking the 6 cubical Tetris pieces, we need to fill the gap from the top of the glass column till the bottom of the 2nd floor. This can be done with high-strength concrete. Different test results has shown that the shrinkage of high-strength concrete is less than that of normal concrete. (Gupta et al., 2009). A mold is placed and liquid concrete is pumped into the mold. Neoprene is placed as an interlayer between the concrete and glass column to prevent direct contact of both materials and also to transport the load from the 2nd floor through the glass column. After the high-strength concrete has been hardened, it needs to be connected to the floor. A suggestion is to use steel bars that starts from the high-strength concrete and goes through the concrete beam of the 2nd floor

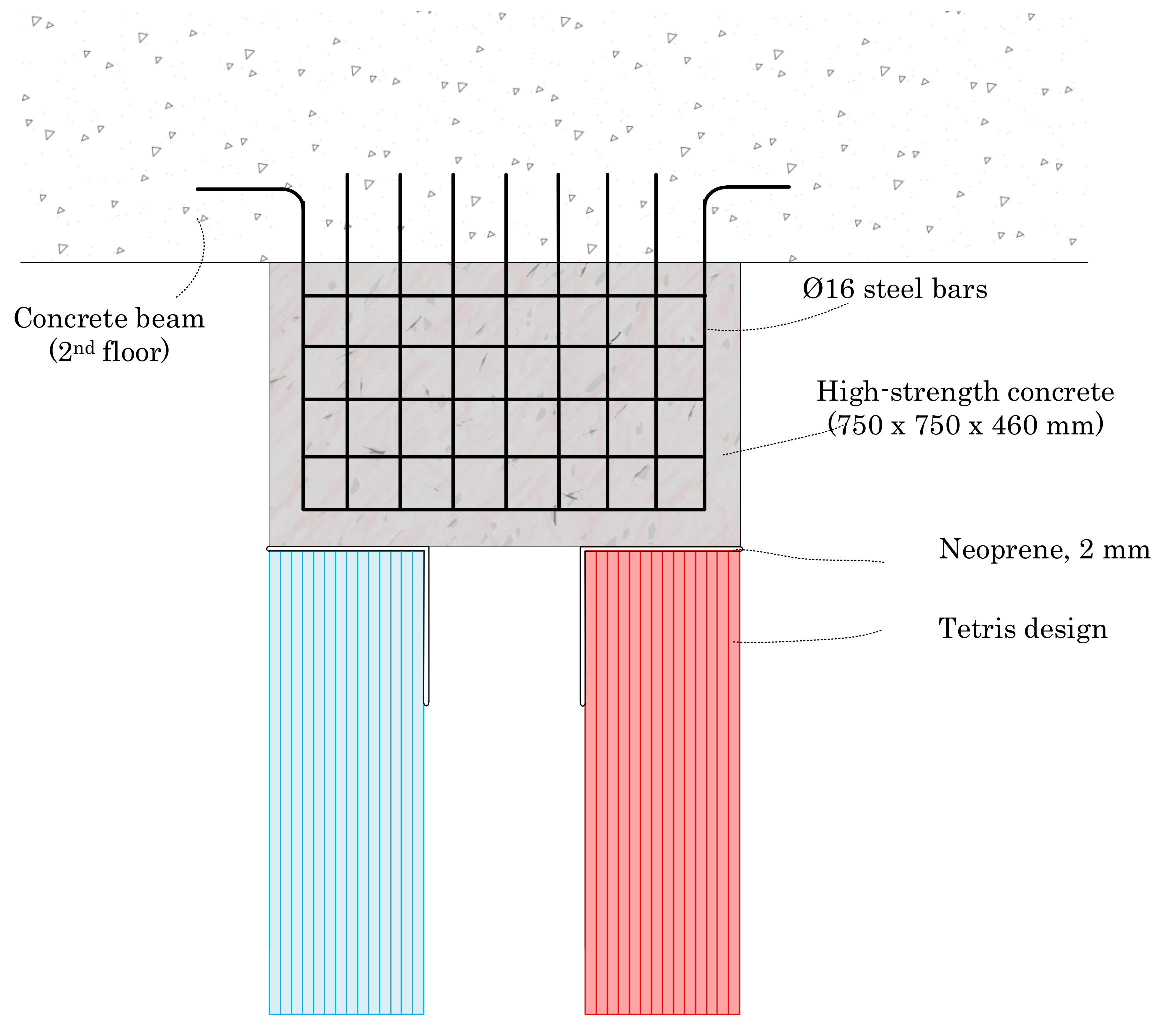

Figure 6.10 Detail of the top.

Bottom

Before we start putting the Tetris shapes, we need to take examine the floor and at the laminated glass parts. The manufacturer will try to make the Tetris shapes as best as they can. However, the surface of the cubical Tetris can still vary a few millimeters to centimeters on micro level. This is also the case with floor as this is not completely flat. Before we place a steel plate on the floor, we need to evenly flat the ground surface. A thin layer of mortar (30 mm) is used for the base of the glass column. It can be flatten out by using a screed which is an aluminum device used to flatten out smooth, wet and pasty materials. Now we need to use soft led to make the bottom flat. After this we can start piling up of the first Tetris shapes.

A vertical steel plate is put against the Tetris shapes with a filling of neoprene to avoid direct contact between the materials. This steel plate will protect any direct damage to the base of the glass column. Bolts are used to connect the steel plates of the floor with the concrete beam of the floor below for extra solidity.

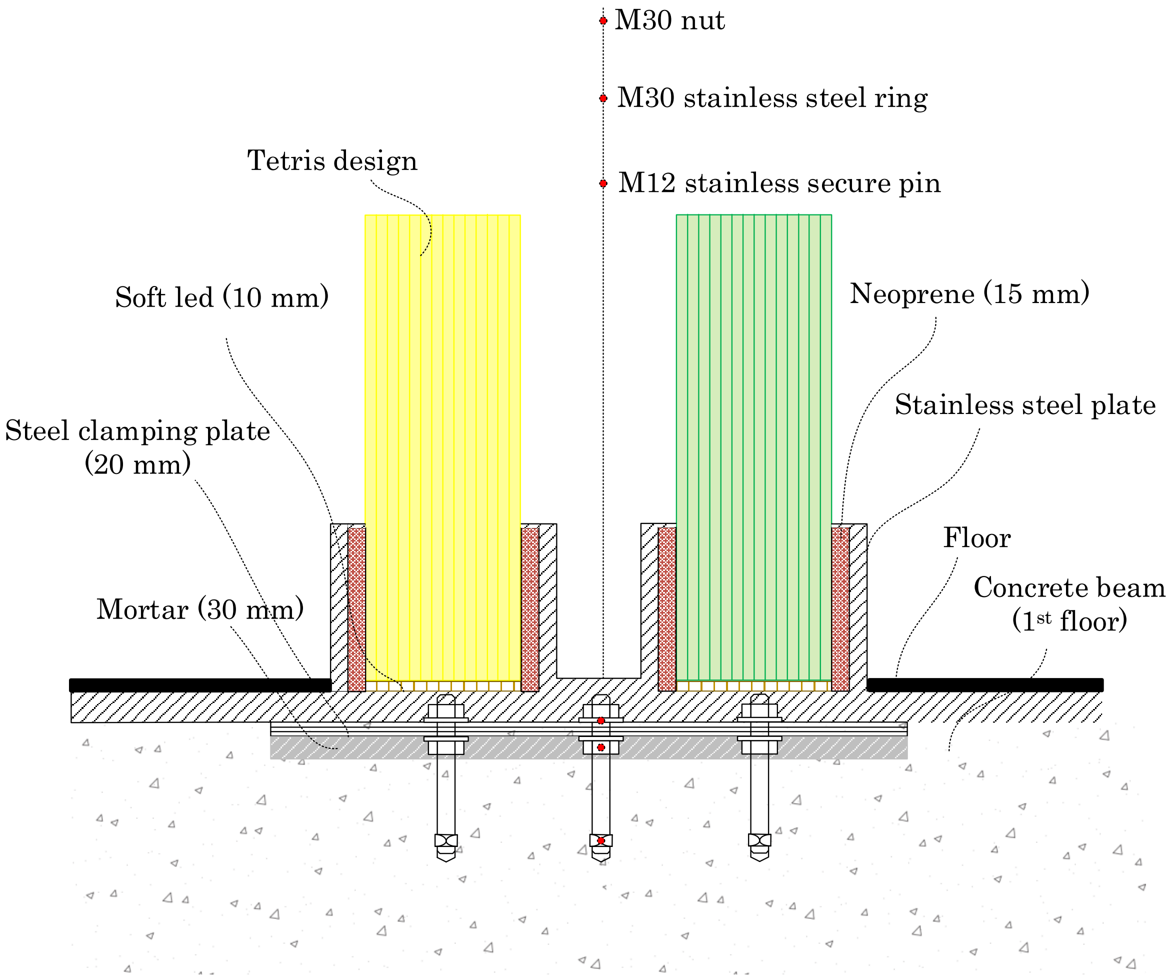

Figure 6.11 Detail of the bottom.

6.6 Transparency

Using stacked laminated glass has two effects for the glass column. One part has the translucent view, this is where you face the multiple slices of the Tetris shape. The other perspective is the transparent view when facing the sides of the Tetris shape. Often you are confronted with one of the two. However, in this case you experience both perspective at once when facing the Tetris column. This results a less transparent view on its whole. I think it is not possible to look through the Tetris column and see the other side perfectly enough as you encounter 28 Tetris slices (14 x 2). This reduces the view drastically.

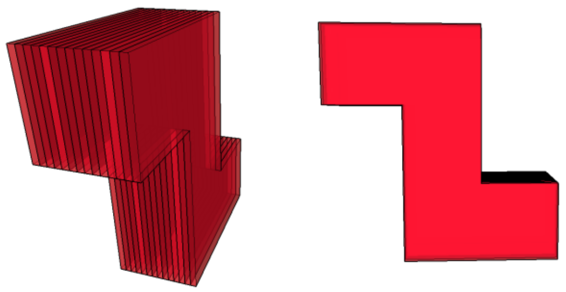

Figure 6.12 Translucent view (left) and transparent view (right).

6.7 Safety

The Tetris column can also be considered a strong massive column thanks to its own weight of approximately 10.000 kg. It can carry high amount of load before buckling. If one of the outer plates gets damaged severely, the adjacent plates will take over the load and distribute it through the column. A safety factor of 4 has been implanted in the design as well, which is more than enough.

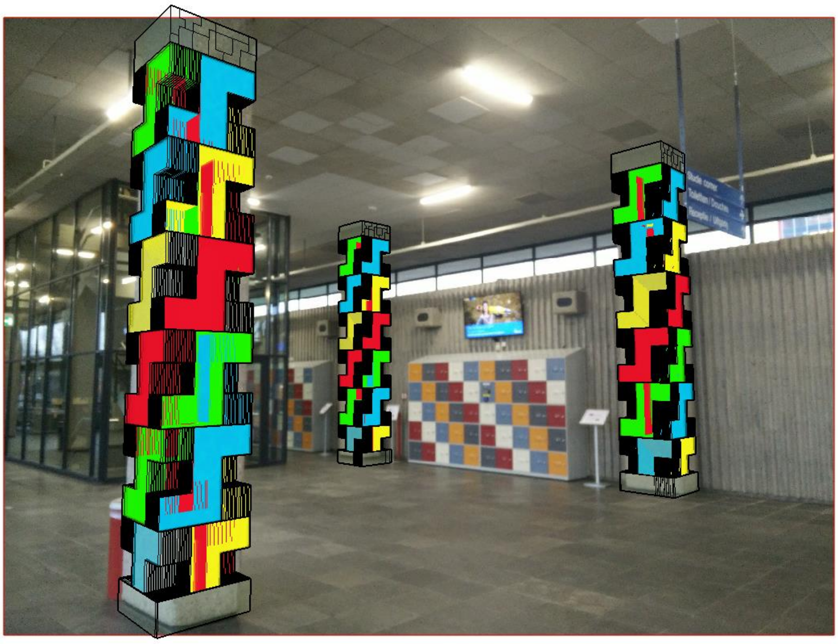

Figure 6.13 The laminated Tetris columns on the first floor in the Civil Engineering faculty at the University of Technology in Delft.

6.8 Conclusion and recommendation

A column is a structure that transfer through compression the load of the above, which is often a floor or a structure. Materials such as concrete, wood or steel are usually used for a column. Visual interpretation are often limited, although this is not the case if you use glass. Glass columns consist of curved or flat glass plates, or extruded standardized profiles. This method limits the form of the column as they are often laminated together with multiple layers and interrupt the transparency. Is there another way to produce glass column?

The design part was very fun due the fact it gave me the freedom to work on a product which is not generally used for a column. The outside-the-box thinking has given me some interesting ideas such as the Tetris design.

You can use different shapes, colors and sizes to stack them together to create a column. For this design I used one shape with four colors, but the possibilities are almost endless.

I originally wanted to use cast glass for my design, but after the discussion with my supervisors it seemed more efficient to work with laminated glass. If we compare the manufacturing time and cost, it was definitely the better option. I cannot imagine how long it would take to anneal one Tetris shape of this size and to replace all the 60 columns of faculty. 1440 Tetris shapes are needed and they all need to be colored as well.

To assemble the Tetris column take not much of an effort. The four different colors serve as an aid and nothing has to be mechanically fasten with bouts or screws. A safety mechanism is also ensured with the load being transferred to adjacent laminated pieces.

To answer my problem statement, thus the conclusion, *'Examine the plausibility of using cast glass elements as an answer to the current limitations in shape and transparency mentioned above.'.* It is definitely possible to use cast glass elements to build the Tetris shape, but the disadvantages are time and money. Therefore, laminated glass is also a great solution. The scores on the matrices that I used a few times in the research is also subjectively. There is no definitive answer to which method is the best a glass column as this all depends on the project. Luckily, in this case, I did not used any crazy shapes, which would definitely change the outcome of this whole research.

I learned a lot in the past weeks during my research and I really do think that maybe in the not too distant future we see more glass columns used in buildings and structures. We are still in an early phase with glass column, however the first steps are already taken.

My recommendation is not to replace the existing concrete columns with the price as the main factor. I did not expect that the costs is so high for a Tetris column. From an architectural view the Tetris column is definitely an improvement of the existing columns. I don't think anyone would quickly spend €13.075.290 (€217.932 x 60 columns) on replacing the columns.

Literature

List of figures

List of tables

Books, journals and websites

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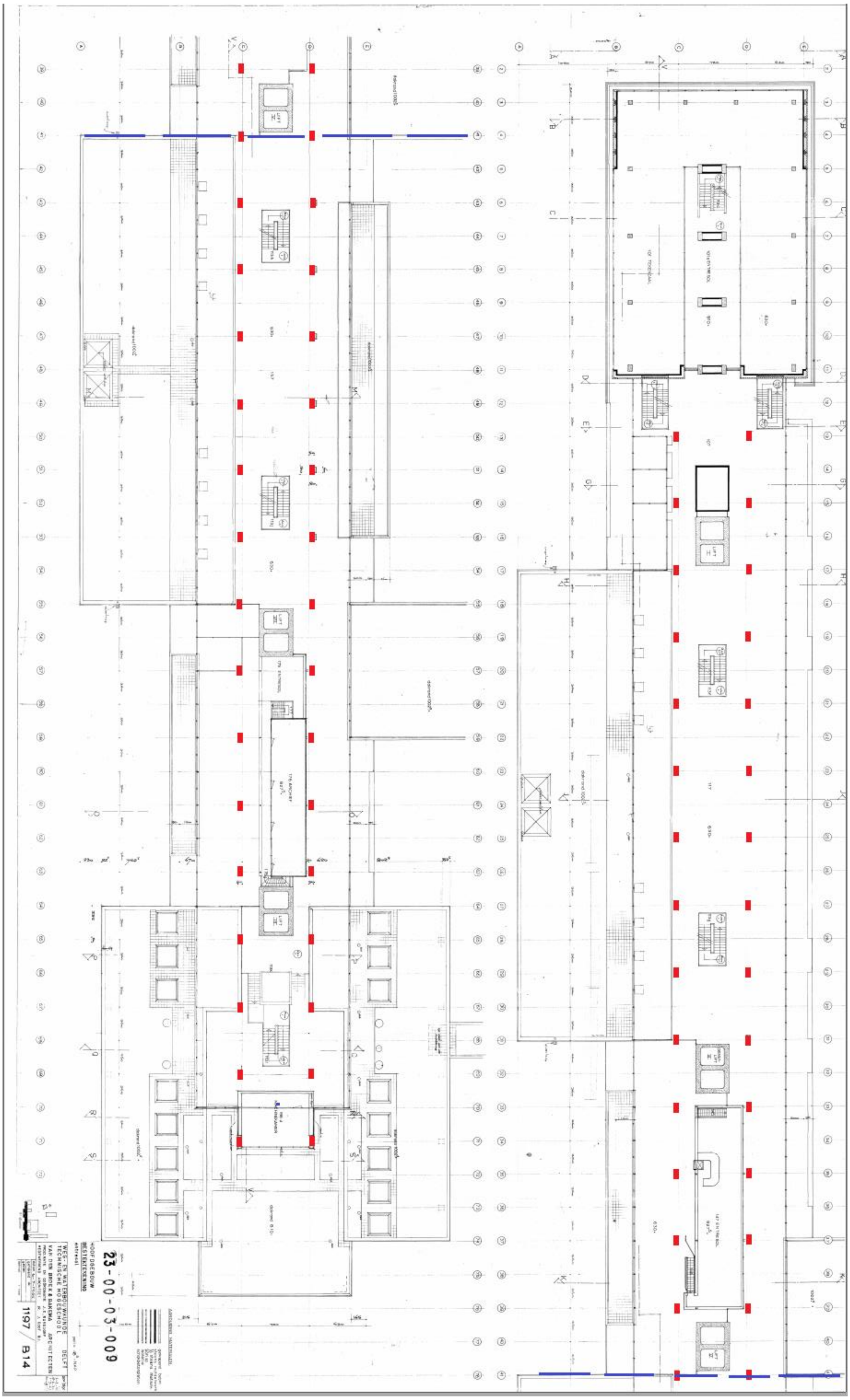
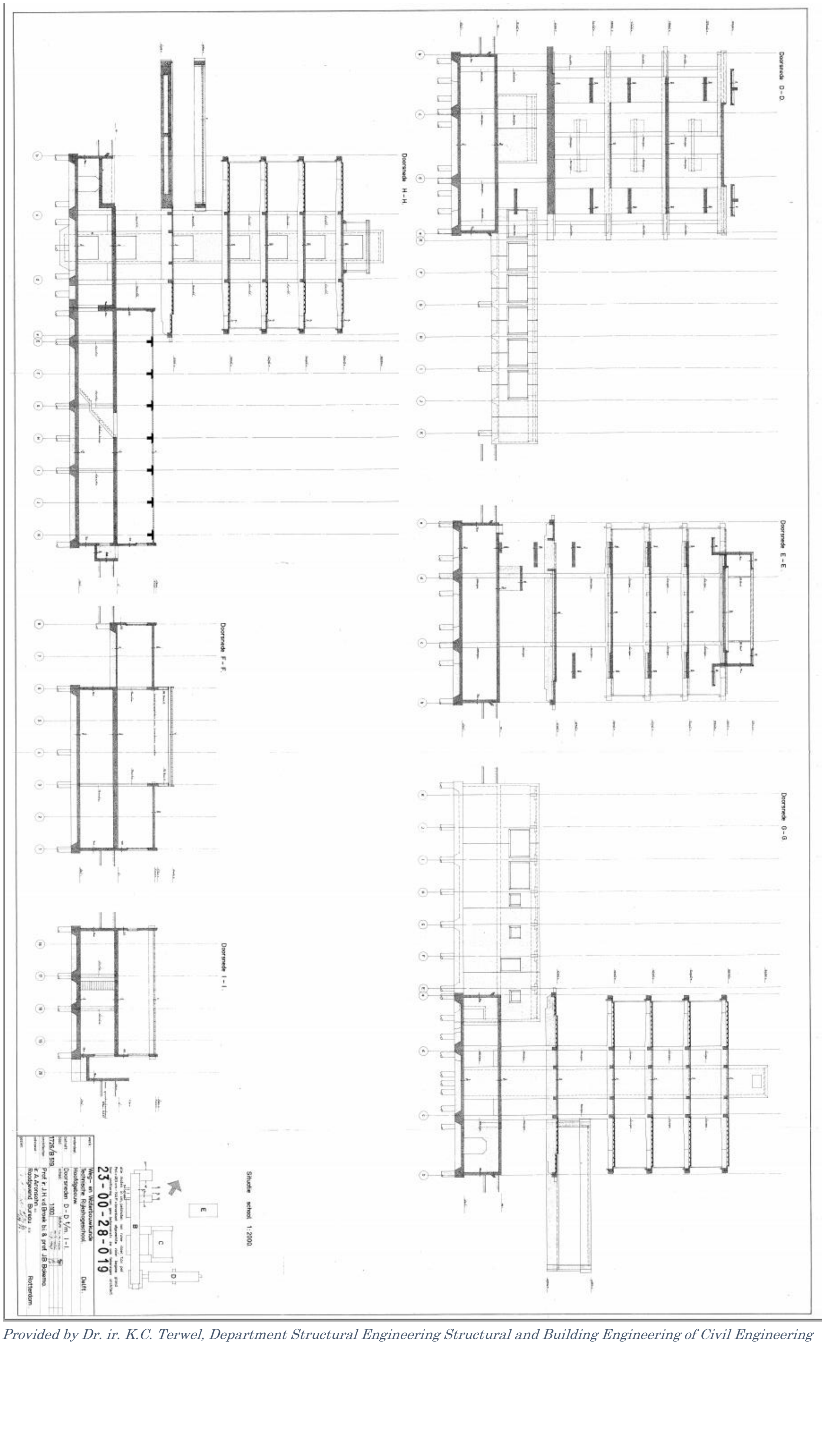
Appendix – A – Blueprint of Civil Engineering at the University of Delft



Provided by Dr. ir. K.C. Terwel, Department Structural Engineering Structural and Building Engineering of Civil Engineering

Appendix – B – Blueprint of Civil Engineering at the University of Delft, cross-section



Provided by Dr. ir. K.C. Terwel, Department Structural Engineering Structural and Building Engineering of Civil Engineering

Meeting Minutes
20-11-2017
14:00

Call to order

- A meeting was held at Building 23 Room B23-S2 1.36 on Monday 20th November.

Attendees

- Attendees included Yat Long Liu and Rob Nijsse.

Members not in attendance

- Members not in attendance included Telesilla Bristogianni.

Discuss last week's actions

- Not available

Proceedings

- Project Initiation Documentation approved, no corrections needed
- Check repository → Robert Akerboom (BK) and Eline Ouwerkerk (CT)
- Make 4-10 concepts and grade them (matrix system), deadline = Monday 4th December

To submit next time

- Draft of thesis by the end of the week (26-11-2017), further communications will be done through mail

Next meeting

- In the week of Monday 4th December to Friday 8th December

Meeting Minutes 07-12-2017 14:00

Call to order

- A meeting was held at Building 23 Room B23-S2 1.36 on Thursday 7th December.

Attendees

- Attendees included Telesilla Bristogianni , Yat Long Liu and Rob Nijsse.

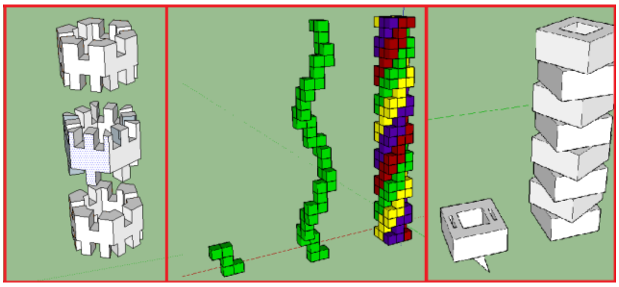
Members not in attendance

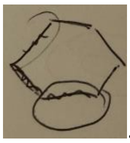
- None

Discuss last week's actions

- Background information and research about glass and come up with three designs.

Proceedings

- Discussed the three design: stacked, Tetris and rotation
- 
- Design 1
  Nijsse: Don't use sharp edges, use the plant as inspiration → the cross section. Little tubes around the perimeter. They are coupled (not all going up), making them much stronger. Make round shapes (more beautiful for an architect). Pay attention to the casting concept, what is feasible and what not?
  Bristogianni: Use a cactus as an inspiration, inside the structure looks like a honeycomb. Consider the height of the interlocks. Use SOLIDWORKS for

calculations. Current design is too complicated to make a mold for → design suggestion: .
3 sides interlocks and 3 sides are flat. → suggesting a round(er) shape.

- Design 2
  Nijsse: Useful shape → you can make the whole column with one single shape. Unique and elegant. The challenge is make something beautiful. The first 3 meters could be solid.
  Bristogianni: Putting cups at the empty corners, the voids. Interesting shape. Not necessary cast glass → float glass also possible, cut it and laminate it.
  In terms of safety → laminate glass is a good choice. At some parts you have transparency and some parts translucent.
- Design 3
  Nijsse: During time limit, proposed to do stick to the first 2 designs and research it.

To submit next time

- Work out the first design with the plant as inspiration.
- No adjustments needed for the second design, already passed the design phase.
- Make a selection criteria, apply to both and choose the best one.
- Pay attention to the buckling load, secondary system, sizing, area needed, weight of the components, producing issues (cooling down), 'make-ability' of cast glass.
- Submit the results before the meeting, ultimately Wednesday 13th December afternoon.

Next meeting

- Building 23 Room B23-S2 1.36 on Thursday 14th December at 14:30

Meeting Minutes 04-01-2018 10:00

Call to order

- A meeting was held at Building 23 Room B23-S2 1.36 on Thursday 4th January.

Attendees

- Attendees included Telesilla Bristogianni , Yat Long Liu and Rob Nijsse.

Members not in attendance

- None

Discuss last week's actions

- Choose one design (based on the scores), make a detail drawing of the connection between the top and the bottom of the column, check the buckling load.

Proceedings

- Presented the numbers of the total load and buckling load. Use a concrete column as a reference. Glass has a Young's modulus of 7 times more than concrete. This way you get a 'feel' for the numbers. The compressive force of glass is also stronger. The whole question is how do you solve the tension? This only occurs when there is buckling going on. Solution → safety factor of 4 to stay away from the buckling. Otherwise you will have tensile stress at the outer parts. Stay away from tension.
- The installation of the column. They will make the column as best as they can, but it can still vary a few millimeters or centimeters → gap. Solution → use high strength concrete that does not shrink to fill the gap. It can take all the shape you like and correct it.
  The 3 problems are: how to get the current concrete column out in a safe way, how to put the glass column and how make the it connect with the top and bottom. Work it out in detail and write the procedure ('first we make a temporary

column, put a jack/vijzel (NL) in between, lift up the floor, take away the column, polish the parts, install the detail, build up the tetris, fill the gap with concrete, wait the concrete till it is hardened, unload the jacks, done')

- The details of the top and bottom of the column.
  Bottom, can't just put a steel plate on a concrete, because it is not evenly flat on micro level. Slather a thin layer of mortar (30 mm) for the base of the column, smoothing it out using a screed. A screed is an aluminum device used to flatten out and smooth wet, pasty materials. Use soft led to make the bottom flat and then start building it up. Put neoprene (artificial rubber, 100 mm) between the glass and steel on the sides to avoid direct contact, they are not friends.
- Connection of the laminated float glass. They interlock with each other (Tetris). Procedure: make a water jet cut and send it to the person who does it. The water pressure cuts it the form you want. Use a thin layer of polyurethane (2 mm) which is capable of taking high load. There are a different hardness, which dictate the compression stresses.
- Colors → easy to assemble. Each piece has its own color. Very expensive to put in into glass. Put color into the interlayer → rolls (https://www.vanceva.com/)

To submit next time

- Work out the details
- Amount of Tetris elements needed for the column and dimensions→ Telesilla

Next meeting

- Contact Telesilla Bristogianni